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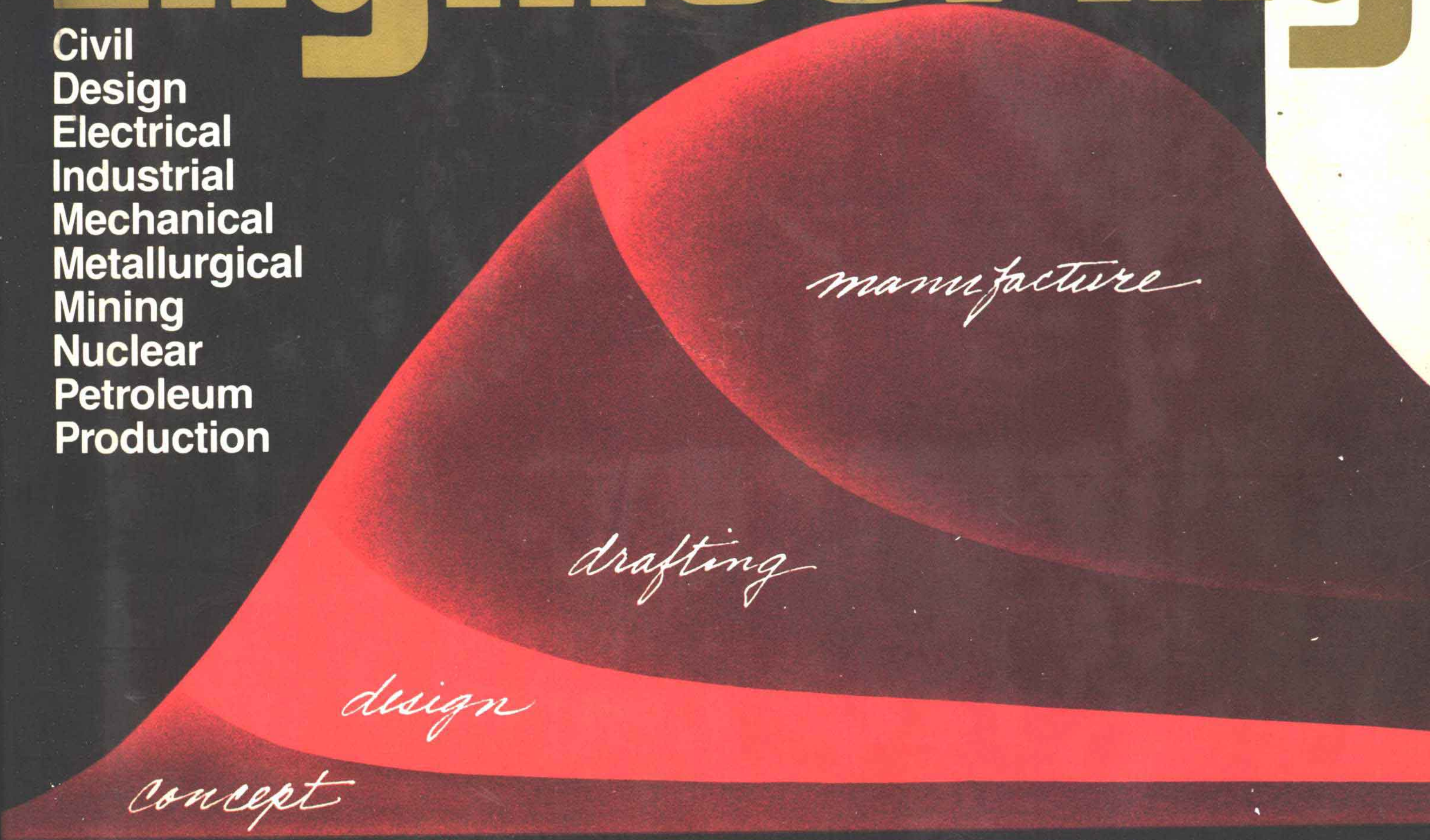

Engineering

Sybil P. Parker
EDITOR IN CHIEF

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Preface

The profession of engineering integrates a spectrum of knowledge extending from the pure physical sciences to the most advanced and specialized technologies. As a widely pervasive pursuit, both as art and science, engineering touches almost every facet of human life and can be said to have created the physical structure of civilization.

Historically, engineering evolved from ancient practices concerned primarily with military endeavors into a multidisciplinary profession with many subdivisions and specialized branches. Civil engineering, for example, gained distinction as a specialty in the mid-18th century, when it was broadly described as being composed of individuals who dealt with the construction of roads, bridges, waterways, harbors, and drainage systems. Today, there are highway engineers, coastal engineers, sanitary engineers, structural engineers, and drainage engineers, to name but a few specializations of civil engineering. Other major branches of engineering have followed a similar pattern of specialization in modern practice.

These changes reflect the increased interrelationship between science and technology, particularly during the 20th century as the time between scientific discoveries and their application has become progressively shorter. Discoveries in solid-state physics which brought about the huge development of electronics —from transistors to microchips—placed new demands on electrical engineers in the area of computers. Zero-gravity technology, made accessible by the space shuttle, will have a growing impact on metallurgical and materials engineers concerned with the manufacture of new alloys and other advanced materials. Turbines and jet engines created new problems for mechanical engineers in terms of thermodynamics and fluid mechanics. Increasing demands for energy, concerns about environmental protection, and the growing awareness of technological risks have, in general, considerably expanded the range of engineering responsibilities. The discovery of superconductivity, a low-temperature phenomenon occurring in many electrical conductors, challenged the imaginations of electrical and mechanical engineers in developing devices with applications in computers, power transmission, and high-speed levitated trains.

It is obvious from these few examples that the scope of engineering is vast and is based on broad scientific understanding. Cooperation between specialists in all fields of science and engineering is therefore the essence of the unified approach to modern engineering education as well as practice. This concept is treated for the first time in a single, comprehensive reference—the *McGraw-Hill Encyclopedia of Engineering*—an interdisciplinary work designed to provide information on ten major branches of engineering. These include civil engineering, design engineering, electrical engineering, industrial engineering, mechanical engineering, metallurgical engineering, mining engineering, nuclear engineering, petroleum engineering, and production engineering. Covered also are the mechanical, electrical, and thermodynamic principles that are basic to all fields of engineering.

The subjects are discussed in more than 690 alphabetically arranged articles selected from the *McGraw-Hill Encyclopedia of Science and Technology* (5th ed., 1982). Hundreds of drawings, tables, charts, graphs, and photographs serve to amplify the text. All information is readily accessible through a detailed analytical index of 6000 entries and by the use of cross-references. Bibliographies provide information on selected further readings for most entries.

In choosing the articles, we are indebted to the Project Consultant, Prof. E. A. Avallone. Moreover, he and Messrs. Altamuro, Anderson, Bowman, Doscher, Judd, and Pavelic, as Field Consultants on the *Encyclopedia of Science and Technology*, have impressed their high standards on this volume as well.

This Encyclopedia will serve the needs of engineers, students, librarians, technical writers, interested laypersons, and all others concerned with the theory and practice of engineering.

Sybil P. Parker
EDITOR IN CHIEF

McGraw-Hill Encyclopedia of Engineering

Acceleration-Zone refining

Acceleration

The time rate of change of velocity. Since velocity is a directed or vector quantity involving both magnitude and direction, a velocity may change by a change of magnitude (speed) or by a change of direction or both. It follows that acceleration is also a directed, or vector, quantity. If the magnitude of the velocity of a body changes from v_1 ft/sec to v_2 ft/sec in t sec, then the average acceleration a has a magnitude given by Eq. (1). To designate it fully the direction should be given, as well as the magnitude. *See* VELOCITY.

$$a = \frac{\text{velocity change}}{\text{elapsed time}} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{\Delta v}{\Delta t} \qquad (1)$$

Instantaneous acceleration is defined as the limit of the ratio of the velocity change to the elapsed time as the time interval approaches zero. When the acceleration is constant, the average acceleration and the instantaneous acceleration are equal.

If a body, moving along a straight line, is accelerated from a speed of 10 to 90 ft/sec in 4 sec, then the average change in speed per second is $(90-10)/4 = 20$ ft/sec in each second. This is written 20 ft per second per second or 20 ft/sec^2. Accelerations are also commonly expressed in meters per second per second (m/sec^2), or in any similar units.

Whenever a body is acted upon by an unbalanced force, it will undergo acceleration. If it is moving in a constant direction, the acting force will produce a continuous change in speed. If it is moving with a constant speed, the acting force will produce an acceleration consisting of a continuous change of direction. In the general case, the acting force may produce both a change of speed and a change of direction. [R. D. RUSK]

Angular acceleration. This is a vector quantity representing the rate of change of angular velocity of a body experiencing rotational motion. If, for example, at an instant t_1, a rigid body is rotating about an axis with an angular velocity $\boldsymbol{\omega}_1$, and at a later time t_2, it has an angular velocity $\boldsymbol{\omega}_2$, the average angular acceleration $\bar{\boldsymbol{\alpha}}$ is given by Eq. (2),

$$\bar{\boldsymbol{\alpha}} = \frac{\boldsymbol{\omega}_2 - \boldsymbol{\omega}_1}{t_2 - t_1} = \frac{\Delta \boldsymbol{\omega}}{\Delta t} \qquad (2)$$

expressed in radians per second per second. The instantaneous angular acceleration is given by $\boldsymbol{\alpha} = d\boldsymbol{\omega}/dt$.

Consequently, if a rigid body is rotating about a fixed axis with an angular acceleration of magnitude α and an angular speed of ω_0 at a given time, then at a later time t the angular speed is given by Eq. (3).

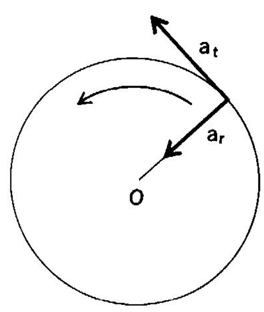
$$\omega = \omega_0 + \alpha t \qquad (3)$$

A simple calculation shows that the angular distance θ traversed in this time is expressed by Eq. (4).

$$\theta = \bar{\omega} t = \left[\frac{\omega_0 + (\omega_0 + \alpha t)}{2}\right] t = \omega_0 t + \tfrac{1}{2}\alpha t^2 \qquad (4)$$

In the figure a particle is shown moving in a circular path of radius R about a fixed axis through O with an angular velocity of $\boldsymbol{\omega}$ radians/sec and an angular acceleration of $\boldsymbol{\alpha}$ radians/sec^2. This particle is subject to a linear acceleration which, at any instant, may be considered to be composed of two components: a radial component $\mathbf{a}_r$ and a tangential component $\mathbf{a}_t$.

ACCELERATION



Radial and tangential accelerations in circular motion.

Radial acceleration. When a body moves in a circular path with constant linear speed at each point in its path, it is also being constantly accelerated toward the center of the circle under the action of the force required to constrain it to move in its circular path. This acceleration toward the center of path is called radial acceleration. In the figure, the radial acceleration, sometimes called centripetal acceleration, is shown by the vector $\mathbf{a}_r$. The magnitude of its value is v^2/R, or ω^2/R, where v is the instantaneous linear velocity. This centrally directed acceleration is necessary to keep the particle moving in a circular path.

Tangential acceleration. The component of linear acceleration tangent to the path of a particle

subject to an angular acceleration about the axis of rotation is called tangential acceleration. In the figure, the tangential acceleration is shown by the vector $\mathbf{a}_t$. The magnitude of its value is αR. *See* ACCELERATION ANALYSIS: ROTATIONAL MOTION.
[C. E. HOWE/R. J. STEPHENSON]

Acceleration analysis

A mathematical technique, often done graphically, by which accelerations of parts of a mechanism are determined. In high-speed machines, particularly those that include cam mechanisms, inertial forces may be the controlling factor in the design of members. An acceleration analysis, based upon velocity analysis, must therefore precede a force analysis. Maximum accelerations are of particular interest to the designer. Although an analytical solution might be preferable if exact maxima were required, graphical solutions formerly tended to be simpler and to facilitate visualization of relationships. Today, for advanced problems certainly, a computer solution, possibly one based on graphical techniques, is often more effective and can also produce very accurate graphical output. *See* FORCE; FORCE ANALYSIS; MECHANISM.

Accelerations on a rigid link. On link OB (Fig. 1*a*) acceleration of point B with respect to point O is the vector sum of two accelerations: (1) normal acceleration A^n_{BO} of B with respect to O because of displacement of B along a path whose instantaneous center of curvature is at O, and (2) tangential acceleration A^t_{BO} of B with respect to O because of angular acceleration α.

For conditions of Fig. 1*a* with link OB rotating about O at angular velocity ω and angular acceleration α, the accelerations can be written as Eqs. (1) and (2). The vector sum or resultant is A_{BO} (Fig. 1*b*).

$$A^n_{BO} = (OB)\omega^2 = V_B^2/(OB) \quad (1)$$

$$A^t_{BO} = (OB)\alpha \quad (2)$$

Accelerations in a linkage. Consider the acceleration of point P on a four-bar linkage (Fig. 2*a*) with $\alpha_2 = 0$ and hence $\omega_2 = k$, the angular velocity of input link 2. First, the velocity problem is solved yielding V_B and by Fig. 2*b*, V_{PB}. Two equations can be written for A_P; they are solved simultaneously by graphical means in Fig. 2*c* by using Fig. 2*b*; that is, normal accelerations of P with respect to B and D are computed first. Directions of tangential acceleration vectors A^t_{PB} and A^t_P are also known from the initial geometry. The tip of vector A_P must lie at their intersection, as shown by the construction of Fig. 2*c*. *See* VELOCITY ANALYSIS.

ACCELERATION ANALYSIS

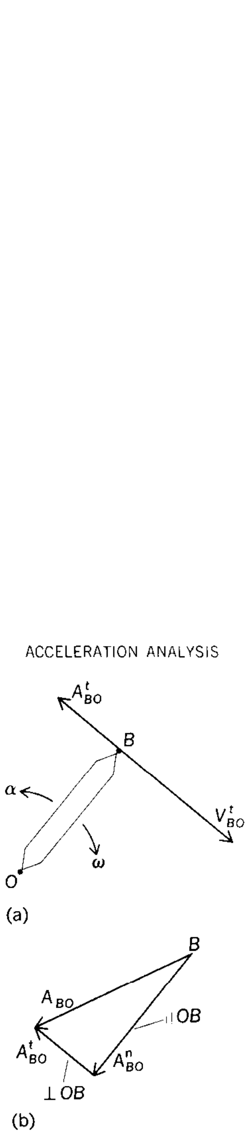


Fig. 1. Elementary condition. (*a*) Point *B* on rigid member rotates about center *O*. (*b*) Vector diagram shows normal, tangential, and resultant accelerations.

Explicitly, acceleration A_P of point P is found on the one hand by beginning with acceleration A_B of point B, represented by Eq. (3). To this acceleration is added vectorially normal acceleration A^n_{PB} and tangential acceleration A^t_{PB}, which can be written as Eq. (4). Also for link 2, $\alpha_2 = 0$ and $A^t_B = 0$; and A_B need not be split up.

$$A_P = A_B \leftrightarrow A_{PB} \quad (3)$$

$$A_P = A_B \leftrightarrow A^n_{PB} \leftrightarrow A^t_{PB} \quad (4)$$

On the other hand, A_P can also be expressed as Eq. (5), or in Fig. 2*c*. The meet of the two tangential

$$A_P = A^n_P + \rightarrow A^t_P \quad (5)$$

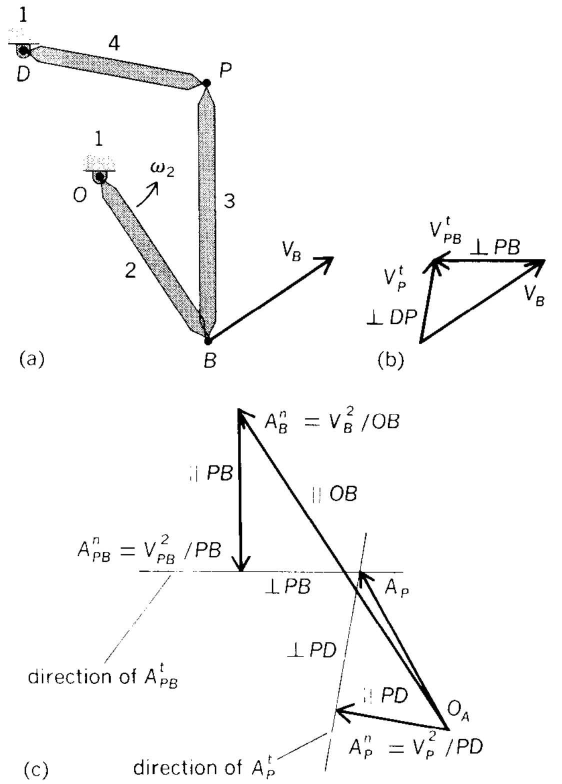


Fig. 2. Four-bar linkage. (*a*) Given are the linkages 2, 3, and 4 between fixed supports 1-1 and the velocity of point *B*, $\omega_2 = 0$. (*b*) Vector polygon is used to determine the velocity at point *P*. (*c*) Graphic solution then finds acceleration at *P*.

components defines the tip of A_P. This problem illustrates the generalization that any basic acceleration analysis can be thoroughly performed only after completion of the underlying velocity analysis.

Acceleration field. Acceleration is a vector and hence has magnitude and direction but not a unique position. A plane rigid body, such as the cam of Fig. 3*a*, in motion parallel to its plane will possess an acceleration field in that plane differing from, but resembling, a rigid-body velocity vector field.

Every acceleration vector in this field, absolute or relative, makes with its instantaneous radius vector the same angle γ (tangent $\gamma = \alpha/\omega^2$) and is proportional in magnitude to the length of this radius vector (Fig. 3*b*). The acceleration field at any instant is thus defined by four parameters: magnitude and direction of accelerations at any two points on the body.

From an acceleration field defined by a_A and a_B (Fig. 3*c*), one can quickly determine the instantaneous center of zero acceleration. From point A', construct vector $A'A''$ parallel and equal to acceleration a_B, represented by vector $B'B$. The relative acceleration a_{AB} is given by the vector of Eq. (6).

$$a_{AB} = a_A - a_B \quad (6)$$

Angle γ between resultant a_{AB} and line AB is common to all radii vectors; therefore, construct radii vectors through A and through B both at γ (properly signed) to their respective acceleration vectors. These lines intersect at Γ, the center of

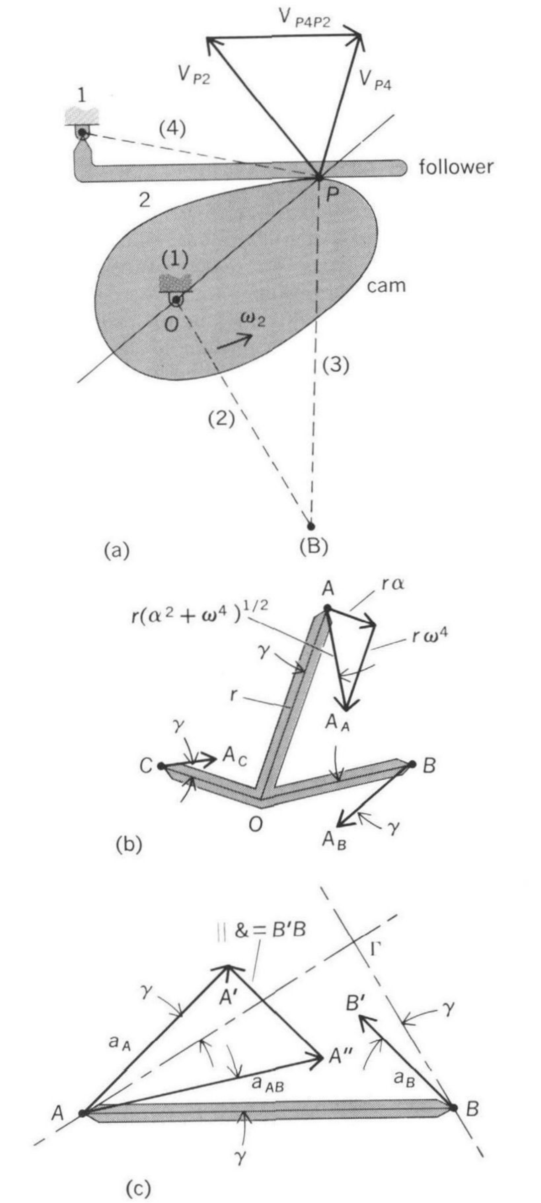


Fig. 3. Accelerations on a cam and follower. (*a*) The cam mechanism. (*b*) The acceleration field about a rigid rotating structure. (*c*) An acceleration field determining an instantaneous center of rotation.

zero acceleration. The geometry contains two similar triangles: $\Delta AB\Gamma$ is similar to $\Delta AA''A'$ because corresponding sides are equally inclined by the angle γ. From these similar triangles comes the generalization that acceleration magnitudes are proportional to radii vectors, just as for the velocity field.

Angle γ ($\tan \gamma = \alpha/\omega^2$) is also used in orientation of acceleration image polygons, especially if the preceding velocity analysis used the image polygon method.

Points not on the same link. Acceleration of follower link 4 of the cam mechanism (Fig. 3*a*) is determined by considering relative accelerations of coincident points not on the same link. Thus point P on link 4, designated P_4, and coincident point P on link 2, designated P_2, have instantaneous velocities, as shown by vectors V_{P_4} and V_{P_2} (Fig. 3*a*). Relative velocity of P_4 with respect to P_2 is $V_{P_4P_2}$ as indicated. Acceleration of P_4 can now be determined by Eq. (7), where the last term is

$$A_{P_4} = A_{P_2} \leftrightarrow A^n{}_{P_4P_2} \leftrightarrow A^t{}_{P_4P_2} \leftrightarrow 2\omega_2 V_{P_4P_2} \qquad (7)$$

the Coriolis component. This component results from referring motion of P_4 on body 4 to P_2 on body 2. Serious errors of analysis can result from omission of the Coriolis component.

Occasionally, mechanisms that appear to require the analysis described in the preceding paragraph may also be analyzed by constructing an instantaneously equivalent linkage shown by dashed lines (2), (3), and (4) in Fig. 3*a*. The instantaneous equivalent linkage is then analyzed by the method of Fig. 2.

Alternative procedures. Other methods may also be used. It is not always necessary to resolve vectors into normal and tangential components; they can be solved by conventional orthogonal component techniques. For points A and B in part *m*, Eq. (8) holds.

$$a_A^{AB} = a_B^{AB} + a_{AB}^{AB} = a_B^{AB} + \omega^2 \cdot AB \qquad (8)$$

A convenient approximate solution is obtained by considering the difference between velocities due to a small angular displacement. This difference in velocities divided by the elapsed short time interval approximates the acceleration. Typically, the angular displacement is taken to be 0.1 radian (0.05 radian either side of the position under study). [DOUGLAS P. ADAMS]

Bibliography: J. Denavit and R. Hartenberg, *Kinematic Synthesis of Linkages*, 1964; C. W. Ham et al., *Mechanics of Machinery*, 4th ed., 1958; D. Lent, *Analysis and Design of Mechanisms*, 2d ed., 1970; A. Sloane, *Engineering Kinematics*, 1966; C. H. Such and C. W. Radcliffe, *Kinematics and Mechanisms Design*, 1978.

Ackerman steering

Differential gear or linkage that turns the two steered road wheels of a self-propelled vehicle so that all wheels roll on circles with a common center. If a vehicle is to turn without lateral skid of any wheel, the center lines of all wheel axles must intersect, when extended, at every instant in a common center about which the vehicle turns (Fig. 1). This requirement is the Ackerman principle of toe out on turns. It is used universally on wheeled vehicles. For straight, forward motion, the front

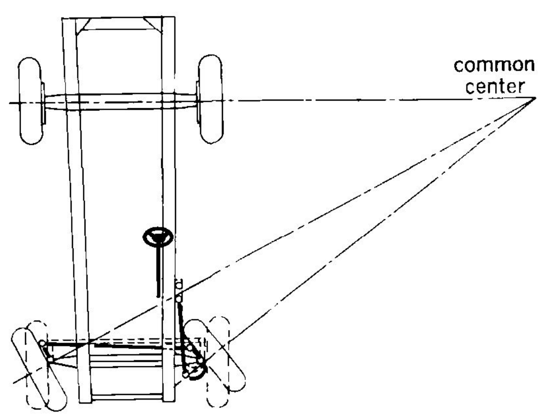


Fig. 1. All wheels turn about a common center.

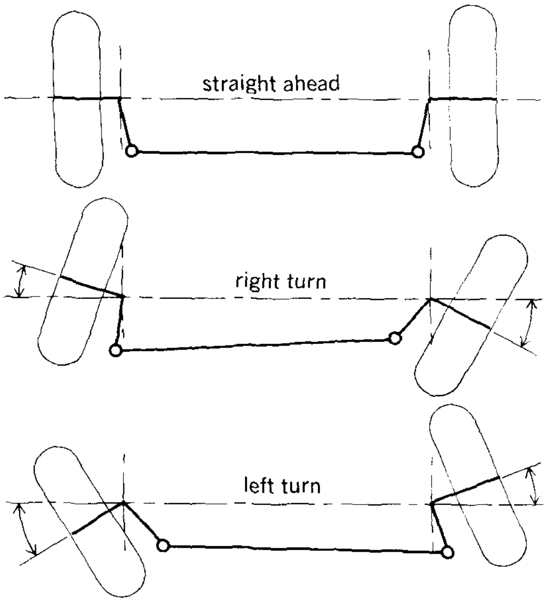


Fig. 2. Inwardly inclined steering knuckles cause the wheels to toe-out on the turns.

wheels are substantially parallel, but as the vehicle enters a curve the inner wheel turns more sharply than the outer wheel. The extreme condition occurs when the vehicle is on a curve of its turning radius. (Turning radius is the arc described by the center of the track made by the outside front wheel of the vehicle when the vehicle makes its shortest turn.)

A common configuration that produces Ackerman steering inclines the knuckle arms inwardly and rearwardly (Fig. 2). The angle of inclination depends on wheelbase and tread of the vehicle. Wheelbase is the distance from front to rear wheels, measured between centers of ground contact. On a vehicle with two rear axles, the rear measuring point is on the ground midway between rear axles. Tread of a vehicle is the distance between front wheels, or between rear wheels, measured from centers of ground contact. *See* AUTOMOTIVE STEERING; FOUR-BAR LINKAGE.

[WILLIAM K. CRESON]

Air and gas compressor

Machines that increase the pressure of a gas or vapor, typically air, by increasing the gas density and delivering the fluid against the connected system resistance. The resistance may be on the suction side, as with vacuum pumps, or on the discharge side, as with air compressors.

Applications. Compressors are typically applied to the operation of pneumatic tools and rock drills, conveying systems, furnace blast systems, ventilation systems, and the inflation of automobile tires. Gas and vapor compressors are represented in the refrigeration, air conditioning, and heat pump fields, where they handle a wide variety of refrigerants near the condensation point, such as Freon, ammonia, carbon dioxide, and sulfur dioxide. Compressors are used in industrial process operations such as nitrogen fixation and gas liquefaction. They are used for repressuring and pumping on natural-gas transmission lines.

The service applications may variously call for suction gas pressures as low as 10^{-8} mm of mercury (with ultrahigh-vacuum pumps) or delivery pressures of 1000 atm (with some chemical process compressors). Volumes handled may be as small as 1 cubic foot per minute (cfm) or as large as 1,000,000 cfm. A wide assortment of machine types is available to meet these diverse conditions and includes positive-displacement units, rotary or reciprocating; free-compression fans and turboblowers, centrifugal and axial; free-compression, hydraulic-, gas-, or vapor-jet pumps; and diffusion and getter pumps. For details and illustrations on many of these types of machines *see* AIR CONDITIONING; COMPRESSOR; FAN; GAS TURBINE; REFRIGERATION; STEAM JET EJECTOR; VACUUM PUMP.

Basic types. The reciprocating compressor is suited to the highest-pressure services, up to about 1000 psi when constructed in three stages with intercoolers. Displacement seldom exceeds 5000 cfm and a 3-ft stroke. Air compressors for the common industrial service of 100 psi are single- or two-stage, selection being determined by economy. Reciprocating compressors are equipped with automatic valves which give accurate timing for the admission and release of gas, and the maintenance of good volumetric efficiency (typically about 75%). Water jackets limit metal temperatures and maintain running clearances on machine parts. On small, portable, and garage-type compressors with free air capacities of about 100 cfm, air jackets may be used.

Rotary compressors are built in capacities as high as 50,000 cfm and compression ratios are usually moderate (less than 3:1). Some designs, such as those with helical lobes or sliding vanes, are good for ratios of 6:1. Rotary compressors are suitable for direct connection to high-speed drivers such as automotive engines and electric motors. Rotary compressors use no valves, and a port construction, with or without liquid seals, controls the cycle kinematics. The rotating lobes are driven through, and maintained in alignment by, gears.

Free-compression devices include fans and blowers, of the centrifugal or axial-flow type, limited to pressure ratios so small that the change in density of the fluid on passage through the unit is negligible. The head gain is customarily measured in inches of water on a manometer, but capacities may be 100–1,000,000 cfm. When higher ratios of compression are required, the multistage centrifugal or axial compressor can be used with pressure ratios as high as 10:1 and frequently operating at speeds of 5000–10,000 rpm.

Jet compressors are free of moving parts; they may be built in sizes as large as 10,000–20,000 cfm, and compression ratios of 5–6:1 in a single stage. They are especially suitable for vacuum service when steam is used as the actuating jet for entrainment of the noncondensible gas. For high vacuum, they are made multistage and equipped with intercoolers and aftercondensers for improved efficiency. [THEODORE BAUMEISTER]

Bibliography: D. W. Anderson, *The Analysis and Design of Pneumatic Systems*, 1976; T. Baumeister (ed.), *Standard Handbook for Mechanical Engineers*, 8th ed., 1978; Trade and Technical Press, *Pneumatic Handbook*, 1978.

Air brake

An energy-conversion mechanism used to retard, stop, or hold a vehicle or, generally, any moving element, the activating force being applied by a difference in air pressure. With an air brake only slight effort by the operator quickly applies full braking force.

An air brake performs the energy conversion like other brakes by friction. The feature that distinguishes an air brake is that the friction-producing device, such as disk or drum, is applied by air in contrast to mechanical, hydraulic, or electrical means. In a particular use the choice between an air brake and any other type of brake depends in part on the availability of an air supply and on the method of brake control. For example, in a motor bus in which compressed air actuates doors, air may also actuate the brakes. On railroad cars compressed air actuates the brakes so that, in the event of a disconnect between cars, air valves can automatically apply brakes on all cars. Air brakes can also be applied mechanically. This allows them to be used while the air pump is not operating; the brakes can be held on even when a vehicle is not in use. Safety regulations require alternate methods of applying brakes. *See* AUTOMOTIVE BRAKE; AUTOMOTIVE VEHICLE; BRAKE; FRICTION.

Because air is compressible, air brakes inherently accommodate to wear, such as in brake shoes. Also, because the force with which brakes are applied depends on the area of an air-driven diaphragm as well as on air pressure, large forces can be developed from moderate pressures. Air pressure can be accurately regulated and can also be controlled by other forces besides the operator's hand or foot; consequently air brakes can be made to respond to static and dynamic forces that influence the efficiency of brake operation.

A totally different kind of air brake is used on aircraft. Energy of momentum is transferred to the air as heat by an air brake that consists of a flap or other device which produces drag. When it is needed, the braking device is extended from an aircraft wing or fuselage into the airstream.

Typical system operation. In a typical air brake system an air compressor takes in and compresses air for use by the brakes and usually for other air-operated components of the vehicle. The compressor may be fitted with a governor to control the air compression within a preselected range, or an air protection valve may allow air to escape if the preselected input pressure is exceeded. Another alternative is for an air pressure reducing valve to deliver a preselected output pressure. The compressed air is stored in an air brake reservoir until needed. A gage indicates to the operator the pressure within the system.

By means of a foot- or hand-operated brake valve the operator controls application of the brake (see figure). A brake rod from the cylinder diaphragm drives the friction element against the moving surface to provide the braking action. When the operator releases the brake valve, an auxiliary reservoir recharges to full pressure through the triple valve. Also, after the braking action is no longer required, a quick release valve assures rapid discharge of air from the brake cylinder. A relay valve may provide automatic application of a trailer brake in case of breakaway or loss of pressure in the trailer line. A relay valve may also serve as a secondary control unit to accelerate the application and release of air pressure in a part of the system. A safety valve or pressure release unit protects the system against excessive pressure. *See* SAFETY VALVE.

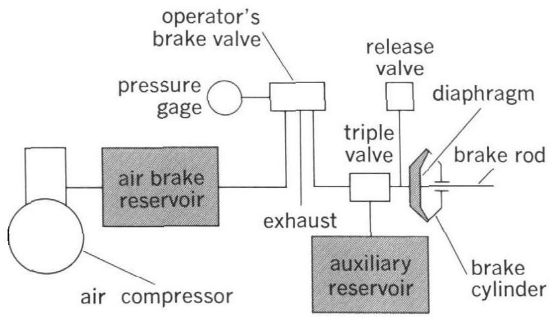


Diagram of air brake. When operator actuates brake valve, pressure to triple valve is reduced. Triple valve then admits compressed air from auxiliary reservoir to brake cylinder, actuating brake rod.

Air brakes may be combined with other systems. In the straight air brake system described above, a mechanical-type brake is actuated by air pressure in a brake cylinder. In a booster system an air-powered master cylinder, controlled by the brake cylinder or chamber, may actuate the brake shoe with added force. In combination with a hydraulic brake system the air system may actuate or assist in control of the hydraulic power unit.

Special features. Air brakes may combine special features. Proportioning valves, by adjusting braking pressures to each actuator cylinder in proportion to axle static and dynamic loads during deceleration, permit shorter stopping distances. The braking force may be balanced with deceleration forces to avoid locking of wheels in an electropneumatic high-speed railroad braking system.

Safety features. To meet international operating requirements for road vehicles, an air brake system may be split. For example, the brake pedal may operate a dual valve with two air lines to the actuator; the actuator may then have two diaphragms, each fully capable of applying the brake. In such a system a warning device alerts the driver if either the service or secondary portion fails. Operation is always arranged to be fail-safe. For example, on railroads, as in the illustrated system, release of pressure in a control line either by the brakeman or by a break in the line actuates the triple valve to connect the auxiliary reservoir to the brake cylinder, with each car carrying its separate auxiliary reservoir.

Critical requirements of air brakes are (1) that the entire system reach pressure stability within the specified minimum differential pressures allowable between separate parts of the system, and (2) that when a valve is transferred or other input change is made to the system, pressure builds up (or reduces) to a new level within a specified minimum time.

Air brakes are required by law on railroads. On passenger trains, where air brakes operate typically at 110 psi, stopping distances are 10% of those produced by hand brakes. Air brakes are widely used on buses and trucks, typically at 80 psi.

Vacuum brake. An alternate form of air brake, the vacuum brake, operates by maintaining low pressure in the actuating cylinder. Braking action is produced by opening one side of the cylinder to the atmosphere so that atmospheric pressure, aided in some designs by gravity, applies the brake. The brake is fail-safe in that it is applied if the vacuum pump stops or if the control line opens. The pump can be the intake of an internal combustion engine.

Vacuum systems are not widely used because of the limited maximum pressure differential. However, one form of automotive power brake provides assistance from a booster cylinder evacuated by the engine air intake.

[FRANK H. ROCKETT]

Bibliography: H. E. Ellinger and R. B. Hathaway, *Automotive Suspension, Steering and Brakes*, 1980.

Air conditioning

The maintenance of certain aspects of the environment within a defined space to facilitate the intended function of that space. Environmental conditions generally encompassed by the term air conditioning include air temperature and motion, radiant heat energy level, moisture level, and concentration of various pollutants, including dust, germs, and gases. Because these environmental factors are associated with air itself, and because air temperature and motion are the factors most readily sensed, simultaneous control of all these factors is called air conditioning, although space conditioning is a better description of the activity.

Comfort air conditioning refers to control of spaces inhabited by people to promote their comfort, health, or productivity. Spaces in which air is conditioned for comfort include residences, offices, institutions, sports arenas, hotels, and factory work areas. Process air conditioning systems are designed to facilitate the functioning of a production, manufacturing, or operational activity. For example, heat-producing electronic equipment in an airplane cockpit must be kept cool to function properly, while the occupants of the cockpit are maintained at comfortable conditions. The environment around a multicolor printing press must have constant relative humidity to avoid paper expansion or shrinkage for accurate registration, while press heat and ink mists must be conducted away for the health of pressmen. Maintenance of conditions within surgical suites of hospitals and in "clean" or "white" rooms of manufacturing plants, where an almost germ- or dust-free atmosphere must be maintained, has become a specialized subdivision of process air conditioning.

Physiological principles. A comfort air conditioning system is designed to help man maintain his body temperature at its normal level without undue stress and to provide him with an atmosphere which is healthy to breathe.

Man's body produces heat at various rates, depending basically upon his weight and degree of activity (see table). Normally more heat is generated than is required to maintain body temperature at a healthful level. Hence, air conditioning always is required to help cool people, never to heat them. Control of a man's body temperature is accomplished by control of the emission of energy from his body by radiation to the space around him, by convection to air currents that impinge on his skin or clothing, by conduction of clothing and objects he touches, and by evaporation of moisture in his lungs and of sweat from his skin. Radiant emission is a function of the amount of clothing (or blankets) worn and the temperature of the surrounding air and objects. Evaporation and convection heat loss are functions of air temperature and velocity. Evaporation is a function, in addition, of relative humidity.

When the amount and type of clothing and the temperature, velocity, and humidity of the air are such that the heat produced by the body is not dissipated at an equal rate, blood temperature begins to rise or fall and discomfort is experienced in the form of fever or chill, in proportion to the departure of body temperature from the normal 98.6°F. Hence, space conditions to promote comfort depend upon the degree of human activity in the space, the amount and type of clothing worn and, to a certain extent, the physical condition of the occupants, because old age or sickness can impair the body's heat-producing and heat-regulating mechanisms.

The heat-dissipating factors of temperature, humidity, and air motion must be considered simultaneously. Within limits, the same amount of comfort (or, more objectively, of heat-dissipating ability) is the result of a combination of these factors in a three-dimensional continuum. Conditions

Estimates of energy metabolism (M) of various types of activity*

Kind of work	Activity	M, Btu/hr
	Sleeping	250
	Sitting quietly	400
Light	Sitting, moderate arm and trunk movements, such as desk work or typing	450–550
	Sitting, moderate arm and leg movements, such as playing organ or driving car in traffic	550–650
	Standing, light work at machine or bench, mostly arms	550–650
Moderate	Sitting, heavy arm and leg movements	650–800
	Standing, light work at machine or bench, some walking about	650–750
	Standing, moderate work at machine or bench some walking about	750–1000
	Walking about, with moderate lifting or pushing	1000–1400
Heavy	Intermittent heavy lifting, pushing, or pulling, such as pick and shovel work	1500–2000
	Hardest sustained work	2000–2400

*Values apply for a 154-lb man and do not include rest pauses.

SOURCE: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., *Handbook of Fundamentals*, 1967.

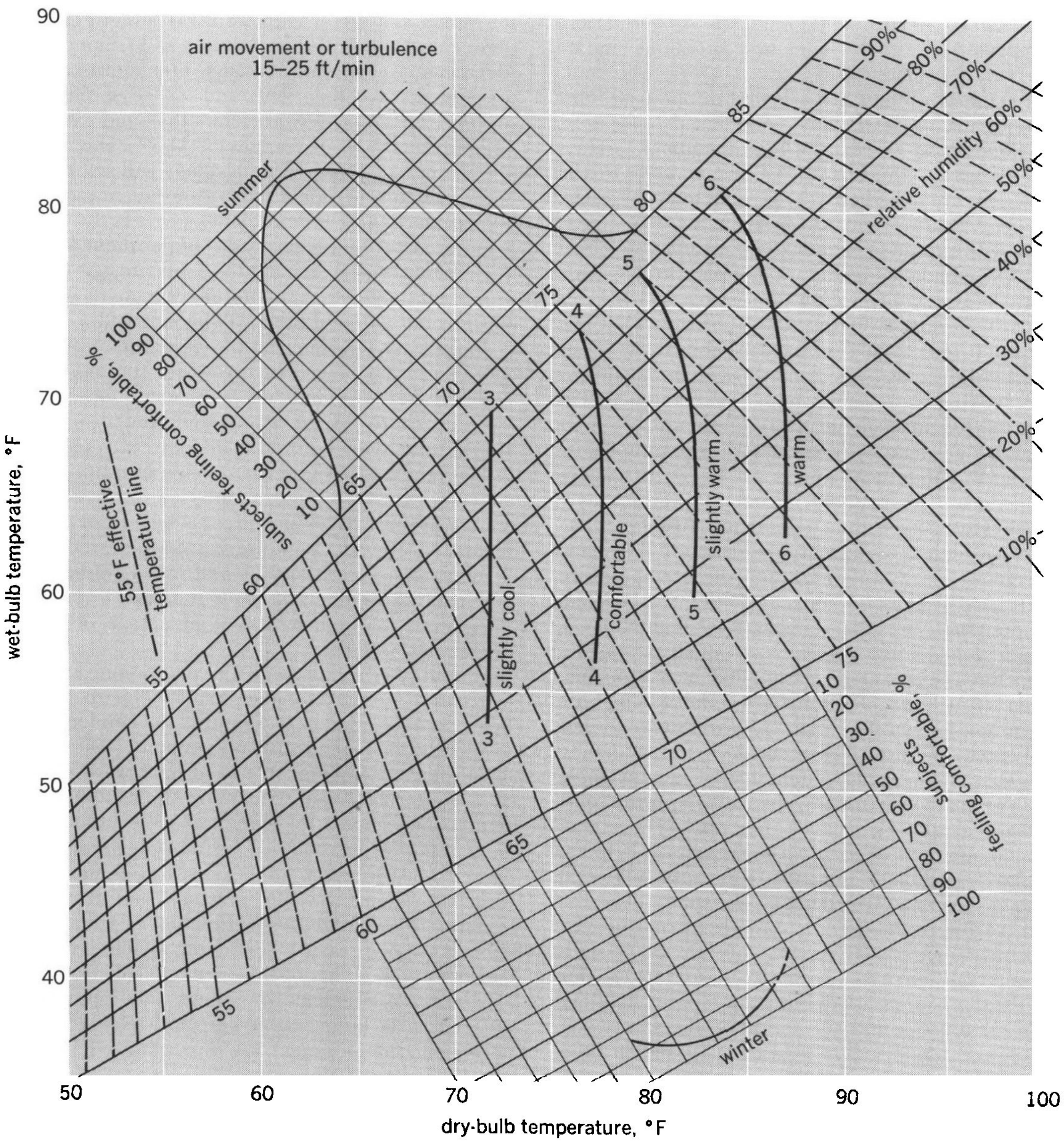


Fig. 1. Revised comfort chart for sedentary adults in the United States. (*American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Handbook of Fundamentals, 1967*)

for constant comfort plot as lines of effective temperature, that is, as combinations that produce equal sensations of comfort (or discomfort). Data on effective temperature have been the subject of intensive research sponsored by American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., and its predecessors since 1923. Figure 1 presents the latest data for sedentary adults in the United States.

In practice most air conditioning systems for offices and institutions, schools, and other light-work spaces are designed to maintain a temperature at 75±°F year-round with relative humidity maintained at 50±% by dehumidification in summer. In winter relative humidities within the conditioned spaces are usually much lower, on the order of 20–30%, as a result of heating relatively dry outside air, and the impracticability of maintaining higher humidities which would cause excessive condensation on cold surfaces, such as window panes. Both conditions correspond closely to comfort requirements; hence, a single year-round thermostat setting is feasible.

The comfort chart (Fig. 1) describes average responses to given environmental conditions. Preferences vary considerably from person to person. For instance, in office buildings most women complain of chill or drafts under conditions where men, clad in business suits, are comfortable. Metabolism rates vary with each individual. Whenever a building budget permits, an engineer designs an air conditioning system that is flexible enough to allow individual adjustment by occupants of both temperature and air motion in the air-conditioned space. Conditions that would satisfy all persons within the same space have yet to be determined.

Calculation of loads. Engineering of an air-conditioning system starts with selection of design conditions; air temperature and relative humidity are principal factors. Next, loads on the system are calculated. Finally, equipment is selected and sized to perform the indicated functions and to carry the estimated loads.

Design conditions are selected on the bases discussed above. Each space is analyzed separately. A cooling load will exist when the sum of heat released within the space and transmitted to the space is greater than the loss of heat from the space. A heating load occurs when the heat generated within the space is less than the loss of heat from it. Similar considerations apply to moisture.

Heat generated within the space consists of body heat, approximately 250 Btu/hr/person, heat from all electrical appliances and lights, 3.41 Btu/hr/watt, and heat from other sources such as gas cooking stoves and industrial ovens. Heat is transmitted through all parts of the space envelope, which includes walls, floor, ceiling, and windows. Whether heat enters or leaves the space depends upon whether the outside surfaces are warmer or cooler than the inside surfaces. The rate at which heat is conducted through the space envelope is a function of the temperature difference across the envelope and the thermal conductance of the envelope. Conductances, which depend on materials of construction and their thicknesses along the path of heat transmission, are a large factor in walls and ceilings exposed to the outdoors in cold winters and hot summers. In these cases insulation is added to decrease the overall conductance of the envelope.

Solar heat loads are an especially important part of load calculation because they represent a large percentage of heat gain through walls and roofs, but are very difficult to estimate because solar irradiation is constantly changing. Intensity of radiation varies with the seasons (it rises to 457 Btu/hr/ft^2 in midwinter and drops to 428 in midsummer). Intensity of solar irradiation also varies with surface orientation. For example, the half-day total for a horizontal surface at 40 degrees north latitude on January 21 is 353 Btu/hr/ft^2 and on June 21 it is 1121 Btu, whereas for a south wall on the same dates comparable data are 815 and 311 Btu, a sharp decrease in summer. Intensity also varies with time of day and cloud cover and other atmospheric phenomena.

The way in which solar radiation affects the space load depends also upon whether the rays are transmitted instantly through glass or impinge on opaque walls. If through glass, the effect begins immediately but does not reach maximum intensity until the interior irradiated surfaces have warmed sufficiently to reradiate into the space, warming the air. In the case of irradiated walls and roofs, the effect is as if the outside air temperature were higher than it is. This apparent temperature is called the sol-air temperature, of which tables are available.

In calculating all these heating effects, the object is proper sizing and intelligent selection of equipment; hence, a design value is sought which will accommodate maximums. However, when dealing with climatic data, which are statistical, historical summaries, record maximums are rarely used. For instance, if in a particular locality the recorded maximum outside temperature was 100°, but 95°F was exceeded only four times in the past 20 years, 95°F may be chosen as the design summer outdoor temperature for calculation of heat transfer through walls. In practice, engineers use tables of design winter and summer outdoor temperatures which list winter temperatures exceeded more than 99% and 97.5% of the time during the coldest winter months, and summer temperatures not exceeded 1%, 2.5%, and 5% of the warmest months. The designer will select that value which represents the conservatism required for the particular type of occupancy. If the space contains vital functions where impairment by virtue of occasional departures from design space conditions cannot be tolerated, the more severe design outdoor conditions will be selected.

In the case of solar load through glass, but even more so in the case of heat transfer through walls and roof, because outside climate conditions are so variable, there may be a considerable thermal lag. It may take hours before the effect of extreme high or low temperatures on the outside of a thick masonry wall is felt on the interior surfaces and space. In some cases the effect is never felt on the inside, but in all cases the lag exists, exerting a leveling effect on the peaks and valleys of heating and cooling demand; hence, it tends to reduce maximums and can be taken advantage of in reducing design loads.

Humidity as a load on an air conditioning system is treated by the engineer in terms of its latent heat, that is, the heat required to condense or evaporate the moisture, approximately 1000 Btu/lb of moisture. People at rest or at light work generate about 200 Btu/hr. Steaming from kitchen activities and moisture generated as a product of combustion of gas flames, or from all drying processes, must be calculated. As with heat, moisture travels through the space envelope, and its rate of transfer is calculated as a function of the difference in vapor pressure across the space envelope and the permeability of the envelope construction. To decrease permeability where vapor pressure differential is large, vapor barriers (relatively impermeable membranes) are incorporated in the envelope construction.

Another load-reducing factor to be calculated is the diversity among the various spaces within a building or building complex served by a single system. Spaces with east-facing walls experience maximum solar loads when west-facing walls have no solar load. In cold weather, rooms facing south may experience a net heat gain due to a preponderant solar load while north-facing rooms require heat. An interior space, separated from adjoining spaces by partitions, floor, and ceiling across which there is no temperature gradient, experiences only a net heat gain, typically from people and lights. Given a system that can transfer this heat to other spaces requiring heat, the net heating load may be zero, even on cold winter days.

Air conditioning systems. A complete air conditioning system is capable of adding and removing heat and moisture and of filtering dust and odorants from the space or spaces it serves. Systems that heat, humidify, and filter only, for control of comfort in winter, are called winter air conditioning systems; those that cool, dehumidify, and filter only are called summer air conditioning systems, provided they are fitted with proper controls to maintain design levels of temperature, relative humidity, and air purity.

Design conditions may be maintained by multi-

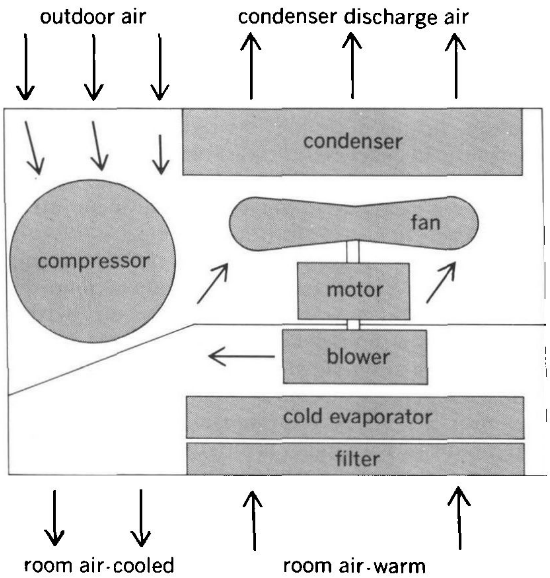


Fig. 2. Schematic of room air conditioner. (*American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Guide and Data Book, 1967*)

ple independent subsystems tied together by a single control system. Such arrangements, called split systems, might consist, for example, of hot-water baseboard heating convectors around a perimeter wall to offset window and wall heat losses when required, plus a central cold-air distribution system to pick up heat and moisture gains as required and to provide filtration for dust and odor.

Air conditioning systems are either unitary or built-up. The window or through-the-wall air conditioner (Fig. 2) is an example of a unitary summer air conditioning system; the entire system is housed in a single package which contains heat removal, dehumidification, and filtration capabilities. When an electric heater is built into it with suitable controls, it functions as a year-round air conditioning system. Unitary air conditioners are manufactured in capacities as high as 100 tons (1 ton of air conditioning equals 12,000 Btu/hr) and are designed to be mounted conveniently on roofs, on the ground, or other convenient location, where they can be connected by ductwork to the conditioned space.

Built-up or field-erected systems are composed of factory-built subassemblies interconnected by means such as piping, wiring, and ducting during final assembly on the building site. Their capacities range up to thousands of tons of refrigeration and millions of Btu per hr of heating. Most large buildings are so conditioned.

Another important and somewhat parallel distinction can be made between incremental and central systems. An incremental system serves a single space; each space to be conditioned has its own, self-contained heating-cooling-dehumidifying-filtering unit. Central systems serve many or all of the conditioned spaces in a building. They range from small, unitary packaged systems to serve single-family residences to large, built-up or field-erected systems serving large buildings.

When many buildings, each with its own air conditioning system which is complete except for a refrigeration and a heating source, are tied to a central plant that distributes chilled water and hot water or steam, the interconnection is referred to as a district heating and cooling system. This system is especially useful for campuses, medical complexes, and office complexes under a single management.

Conditioning of spaces. Air temperature in a space can be controlled by radiant panels in floor, walls, or ceiling to emit or absorb energy, depending on panel temperature. Such is the radiant panel system. However, to control humidity and air purity, and in most systems for controlling air temperature, a portion of the air in the space is withdrawn, processed, and returned to the space to mix with the remaining air. In the language of the engineer, a portion of the room air is returned (to an air-handling unit) and, after being conditioned, is supplied to the space. A portion of the return air is spilled (exhausted to the outdoors) while an equal quantity (of outdoor air) is brought into the system and mixed with the remaining return air before entering the air handler.

Typically, the air-handling unit contains a filter, a cooling coil, a heating coil, and a fan in a suitable casing (Fig. 3). The filter removes dust from both return and outside air. The cooling coil, either containing recirculating chilled water or boiling refrigerant, lowers air temperature sufficiently to dehumidify it to the required degree. The heating coil, in winter, serves a straightforward heating function, but when the cooling coil is functioning, it serves to raise the temperature of the dehumidified air (to reheat it) to the exact temperature required to perform its cooling function. The air handler may perform its function, in microcosm, in room units in each space, as part of a self-contained, unitary air conditioner, or it may be a huge unit handling return air from an entire building. *See* AIR COOLING; AIR FILTER; HUMIDITY CONTROL.

There are three principal types of central air-conditioning systems: all-air, all-water, and air-water. In the all-air system all return air is processed in a central air-handling apparatus. In one type of all-air system, called dual-duct, warm air and chilled air are supplied to a blending or mixing unit in each space. In a single-duct all-air

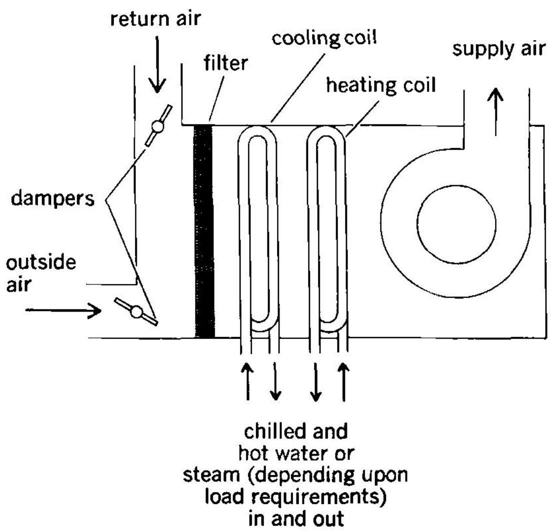


Fig. 3. Schematic of central air-handling unit.

system air is supplied at a temperature for the space requiring the coldest air, then reheated by steam or electric or hot-water coils in each space.

In the all-water system the principal thermal load is carried by chilled and hot water generated in a central facility and piped to coils in each space; room air then passes over the coils. A small, central air system supplements the all-water system to provide dehumidification and air filtration. The radiant panel system, previously described, may also be in the form of an all-water system.

In an air-water system both treated air and hot or chilled water are supplied to units in each space. In winter hot water is supplied, accompanied by cooled, dehumidified air. In summer chilled water is supplied with warmer (but dehumidified) air. One supply reheats the other.

All-air systems preceded the others. Primary motivation for all-water and air-water systems is their capacity for carrying large quantities of heat energy in small pipes, rather than in larger air ducts. To accomplish the same purpose, big-building all-air systems are designed for high velocities and pressures, requiring much smaller ducts.

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Air cooling

Lowering of air temperature for comfort, process control, or food preservation. Air and water vapor occur together in the atmosphere. The mixture is commonly cooled by direct convective heat transfer of its internal energy (sensible heat) to a surface or medium at lower temperature. In the most compact arrangement, transfer is through a finned (extended surface) coil, metallic and thin, inside of which is circulating either chilled water, antifreeze solution, brine, or boiling refrigerant. The fluid acts as the heat receiver. Heat transfer can also be directly to a wetted surface, such as water droplets in an air washer or a wet pad in an evaporative cooler. *See* AIR CONDITIONING.

Evaporative cooling. For evaporative cooling, nonsaturated air is mixed with water. Some of the sensible heat transfers from the air to the evaporating water. The heat then returns to the airstream as latent heat of water vapor. The exchange is thermally isolated (adiabatic) and continues until the air is saturated and air and water temperatures are equal. With suitable apparatus, air temperature approaches within a few degrees of the theoretical limit, the wet-bulb temperature. Evaporative cooling is frequently carried out by blowing relatively dry air through a wet mat (Fig. 1). The technique is employed for air cooling of machines where higher humidities can be tolerated; for cooling of industrial areas where high humidities are required, as in textile mills; and for comfort cooling in hot, dry climates, where partial saturation results in cool air at relatively low humidity.

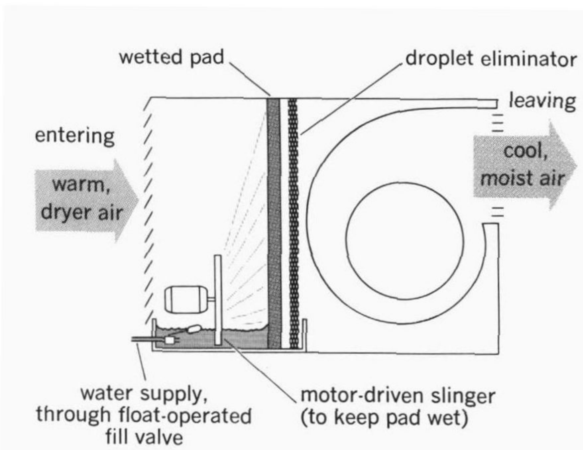

Fig. 1. Schematic view of simple evaporative air cooler.

Air washer. In the evaporative cooler the air is constantly changed and the water is recirculated, except for that portion which has evaporated and which must be made up. Water temperature remains at the adiabatic saturation (wet-bulb) temperature. If water temperature is controlled, as by refrigeration, the leaving air temperature can be controlled within wide limits. Entering warm, moist air can be cooled below its dew point so that, although it leaves close to saturation, it leaves with less moisture per unit volume of air than when it entered. An apparatus to accomplish this is called an air washer (Fig. 2). It is used in many industrial and comfort air conditioning systems, and performs the added functions of cleansing the airstream of dust and of gases that dissolve in water, and in winter, through the addition of heat to the water, of warming and humidifying the air.

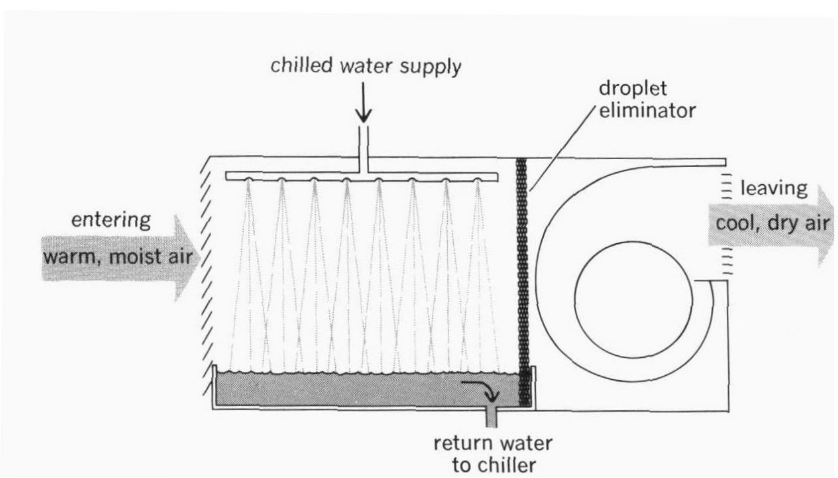

Fig. 2. Schematic of air washer.

Air-cooling coils. The most important form of air cooling is by finned coils, inside of which circulates a cold fluid or cold, boiling refrigerant (Fig. 3). The latter is called a direct-expansion (DX) coil. In most applications the finned surfaces become wet as condensation occurs simultaneously with sensible cooling. Usually, the required amount of dehumidification determines the temperature at which the surface is maintained and, where this results in air that is colder than required, the air is reheated to the proper temperature. Droplets of condensate are entrained in the airstream, removed by a suitable filter (eliminator), collected in a drain pan, and wasted.

In the majority of cases, where chilled water or boiling halocarbon refrigerants are used, aluminum fins on copper coils are employed. Chief advantages of finned coils for air cooling are (1) complete separation of cooling fluid from airstream, (2) high velocity of airstream limited only by the need to separate condensate that is entrained in the airstream, (3) adaptability of coil configuration to requirements of different apparatus, and (4) compact heat-exchange surface.