Kirk-Othmer Encyclopedia of Chemical Technology.

CONVEYING

Conveying is a term used for the transport of bulk solids. Bulk solids conveyors are in large part made up of components that are dimensionally standardized, but fabricated in varying classes of construction to meet operating conditions ranging from light-duty intermittent operation to heavy-duty continuous operation. Conveyors are volumetric machines that transport material fed to them at a controlled rate. This is in contrast to solids feeders that operate under a solids head and control the volumetric flow. By appropriate changes in geometry, most conveyors can be used as volumetric feeders. By addition of appropriate weight sensing and control modules, conveyors can also be used as gravimetric feeders. The selection of the type of conveyor for a specific application is dependent first on the required capacity; second, on the conveying path, ie, horizontal, vertical, or a combination of both; and third, on the handling characteristics of the material.

1. Characterization of Bulk Material

The basis of all bulk conveyor engineering is the precise definition and accurate classification of materials according to individual characteristics under a specific combination of handling conditions (1). Since the late 1960s there has been an extraordinary growth in research into the fundamental properties and behavior of particulate solids. However, as of this writing, it is not possible to predict the handling behavior of a bulk solids material relevant to conditions in a specific conveyor, merely on the basis of the discrete particle properties.

The laws governing gravity flow within channels in silos and bins can be determined by treating the bulk solids as a continuum, where the properties are a continuous function (2). The mass can then be divided indefinitely without losing these defining properties. As a result, the Jenike flow theories, shear tests, and design procedures have been developed that make it possible to design bulk solids storage bins for reliable and predictable flow, with a high degree of success. Boundary conditions within bulk handling systems are considerably different from those within silos, however, so this analysis has not yet produced a useful general correlation for predicting behavior in conveying situations. Although intended primarily for bin design, the Jenike shear tester is often used to measure *relative* flowability of a powder or granular material. The test procedure also includes measurement of the coefficient of friction between a moving bed of material and a stationary wall surface that replicates the wall surface in a silo. The friction values obtained in this manner can be useful for some, but not all, conveyor design situations, because the relative rubbing velocities (about 3 mm/min) used in the test are much lower than those normally encountered in most dry bulk and powder conveying systems (see also Powders, handling).

Industry practice is to describe flow behavior by descriptive terms derived by combining data from empirical bench-top tests and observations of actual conveying systems in operation. This information is then used first, as a guide in the selection of the particular type of conveyor, and second, for determining the design features required for the particular application. Collections of most of this information can be found in the guides published by manufacturers' engineering associations in various countries. These guides contain extensive listings of measured and observed handling characteristics for specific materials. Typical are the publications of the Conveyor Equipment Manufacturers Association (CEMA) (1) in the United States, used primarily for mechanical conveying.

The CEMA publication gives terminology, definitions, and test procedures for measuring and describing 37 characteristics of a material. Each measured characteristic or property is assigned an alpha-numeric classification code designation. Thus the *CEMA Classification Code* provides a convenient method of communication between users and manufacturers of conveying equipment. Other countries have developed similar standardized tests, most of which have been directed towards mechanical conveying. Classification tests for characterizing material, specifically for pneumatic conveyor design applications, are still in the development stage and have not yet been published as a universally accepted standard. The publication by the Engineering Equipment Users Association is often cited (3).

Information on the behavior of bulk materials in conveying equipment is being developed through a number of sources. Extensive research on the characterization of bulk solids and the flow behavior of bulk solids in conveyors and feeders has been published (4). This work includes the design of devices to study and measure the abrasive wear of materials on surfaces that simulate conveyor components using the surface speeds normally encountered in mechanical conveying systems, and abrasive wear on surfaces that simulate silo walls at surface speeds normally encountered during flow. A device to measure the particle attrition that occurs during simulated flow or conveying is also described. Several proprietary devices have been developed from similar work (5). Useful information on the flow behavior of bulk powders and granules can be found in References (6–8).

2. Conveyor Types

2.1. Belt Conveyors

A belt conveyor is made up of an endless fabric or elastomer covered belt that traverses between two or more pulleys, and is supported at intermediate points by idler rolls. These conveyors can handle a wide range of materials, from fine powders to large, lumpy stone and coal. Material can be transported at rates of over 5000 t/h and the conveyors operated at belt speeds ranging from 20 to 300 m/min over very long distances. Versatility, reliability, and range of capacities have made belt conveyors the most commonly used bulk handling conveyors in industry.

A typical belt conveyor arrangement is shown in Figure 1. These conveyors can be arranged horizontally and with inclined or declined sections combined with convex and concave curves. The desired path of travel is limited only by the strength of the belt and the permissible angle of incline or decline for the particular situation.

Bulk materials are sometimes conveyed on flat belts that are supported on horizontal idlers on the carrying and return runs. However, in most industrial systems, in order to increase handling capacity, the conveyor belt is formed into a trough shape after it has been loaded with material, and it is supported along the carrying run by troughing idlers. The most commonly used troughing idler consists of three rolls as shown in Figure **1b** An extensive guide to design and application of belt conveyors is available (9) as are belt conveyor standards (10–12).

Belt-conveying design technology is changing rapidly. Newer methods using computers for dynamic analysis can take the viscoelastic properties of the conveyor belt and the distribution of stresses during startup and shut down into consideration. Analysis is being applied to long conveyor belts and belts with horizontal curves. A description of these design techniques is available (13).

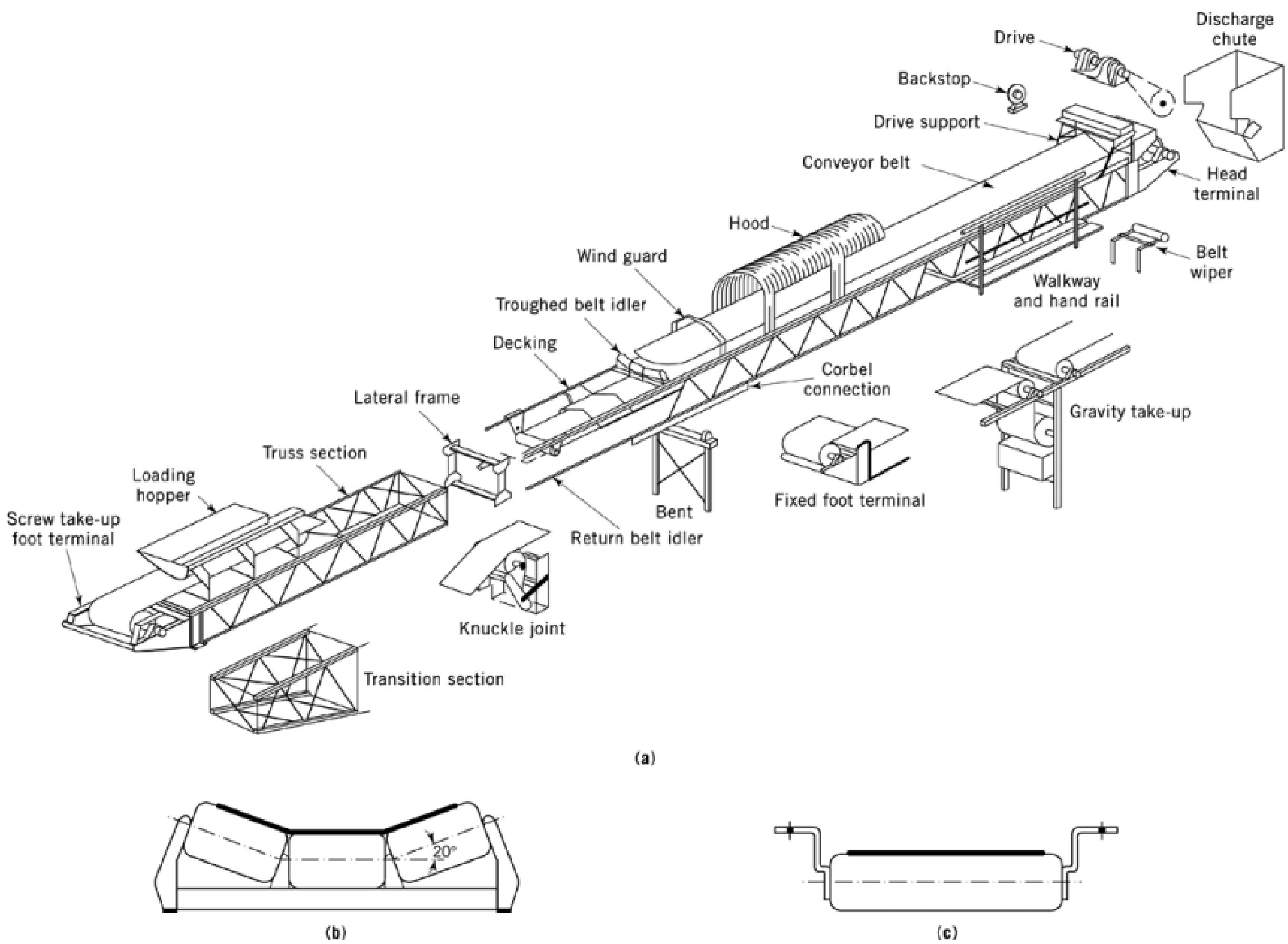

Fig. 1. (**a**) Belt conveyor and support assembly, (**b**) 20° troughing idler, and (**c**) return idler.

2.1.1. Material Characteristics Influencing Design

Materials ranging from fine powders to large lumpy materials, nonabrasive to very abrasive, free-flowing to cohesive, and nonfriable to friable can be handled on properly designed belt conveyors. Very sticky materials can be a problem, however, if these cannot be continuously cleaned from the belt surface.

Material characteristics typically used as criteria for determining the required belt width, the carrying capacity of a particular belt, and the maximum inclination at which the belt can be operated are (*1*) The angle of repose and the angle of surcharge. The angle of repose is the angle which a freely formed heap of bulk material makes with the horizontal. The measured value of this angle, when taken together with observations of particle shape and size, moisture and general flowability, determines what is known in belt conveying technology as the angle of surcharge. This is defined as the angle (to the horizontal) which a material assumes while at rest on a moving conveyor belt. For most materials, the angle of surcharge is usually 5 to 15° less than the angle of repose, but with some very free-flowing materials, it may be 20° less. The angle of surcharge is a basic design parameter for determining the transport capacity of a belt conveyor. Because the cross-sectional area of the heap on the belt is defined by the belt trough geometry and angle of surcharge, the belt speed required for a desired transport rate of a material with a known bulk density can be easily determined. (*2*) The size and proportion of lumps. The larger the lumps and the greater the number, the wider the belt must be to prevent the lumps from spilling over the edge of a horizontal conveyor, and the more likely they are to roll back, or fall over the edge, on an inclined conveyor. (*3*) Fluidizing or air retention properties. Materials that are easily aerated and have long air retention times impose limitations on allowable belt inclinations and belt speeds.

2.1.2. Carrying Idlers

The most commonly used troughed carrying idlers have the outer rolls inclined at either 20, 35, or 45° from the horizontal (see Fig. **1b**). Carrying capacity of the belt increases as the idler angle increases. In the past, construction of multi-ply belts were fairly stiff, and did not allow the belt to conform well to idlers having troughing angles over 20°. The newer belts, having carcasses of various synthetic fiber blends, are more flexible and can be designed to trough at the higher angles (see Fibers). As a result, the 35 and 45° idlers are gaining in popularity. Troughed idlers can be mounted on pivoted supports and spaced at intervals along the conveyor for training or guiding the belt, ie, to keep it centered on the carrying idlers during transient upsets.

The mechanical design of the idler rolls is a function of the particular service under which the conveyor operates. Minimum industrial standards for roll dimensions, bearings, and application criteria for different service conditions have been established (14). Idler life is determined by a combination of factors such as bearings, seals, shell thickness, load density, and the operating environment.

Bearing rating, or bearing life, is the only variable for which laboratory tests can provide standard values. Thus CEMA uses bearings as a guide for establishing idler ratings (9). The term useful life (BU), representing the statistical point in hours where a minimum of 90% of the bearings are expected to be still functional with no increase in torque or noise, is employed. The minimum required load ratings for equal-length roll idlers for service conditions ranging from light duty to heavy duty, based on 90,000 h minimum bearing life at 500 rpm, have been determined for belt widths ranging from 450 to 2500 mm, for 20, 35 and 45° troughing angles, and for flat idlers. These ratings form the basis for the minimum design requirements for CEMA-rated idlers. Actual figures for idlers furnished by manufacturers must be obtained from the idler manufacturer. Whereas bearing life is useful as an indicator of idler life, other factors such as bearing seal effectiveness, may be more important in determining idler life under certain circumstances.

A variety of specialized idlers are available. Examples are plastic disk catenary idlers for handling wet corrosive materials; two roll idlers, where the rolls are oriented in a vee for lighter duty conveying system; and suspended idler supports for severe service. In this last type, three to five idler rolls are linked end-to-end and suspended from conveyor frame stringers to form a caternary that cradles the belt.

Conveyor belts are manufactured in widths up to 2500 mm. The belt represents a substantial part of the initial cost of a belt conveying system and it is the component most susceptible to damage. The typical belt consists of two principal elements: the covers (top and bottom), and the carcass. The primary purpose of the covers is to protect the carcass against environmental effects, wear, and cutting. Covers are natural or synthetic rubber, thermosetting elastomers, and thermoplastic materials. The carcass provides the tensile strength required to start and move the loaded belt, the transverse and longitudinal flexibility needed to allow the belt to both support the load and conform to the shape of the idlers when running empty and to properly wrap around pulleys, and the strength to resist impact forces.

Carcass and cover ratings for belts manufactured in the U.S. have been established by the Rubber Manufacturers Association (RMA) (15). Guidance for specific applications can be found in Reference 9. Similar, but not the same belt rating systems have been established in most other countries.

2.1.3. Carcass Construction

Carcasses are made of one or more plies of a woven fabric bonded together with an elastomeric compound. Woven materials that are used include cotton, rayon, nylon, polyester, aramids, and glass, in the pure form or in blends. The fabrics are constructed with warp yarns that run lengthwise along the belt, and filling (weft) yarns that run crosswise. There are a variety of fabric weaves available for specific applications (15).

Multiple ply belts manufactured in the U.S. were standardized on the basis of tension ratings into a range of MP designations that classified a belt tension rating in pounds per inch per ply, without regard for the type of fiber used. The development of the newer high tenacity synthetic fibers and improvements in belt construction led to a wide variety of belts having load capacities that equal or exceed those of the belts having the MP designation, and do it with fewer plies. As a result, the MP designation is less used. Belt tension ratings are being specified by the manufacturers on the basis of pounds per inch of belt width (PWI) for each particular belt of manufacture.

A more recent development in belt technology has been the solid-woven carcass belts impregnated and covered with poly(vinyl chloride) (PVC) or urethane plastisol. Steel cable belts, made with a single layer of parallel steel cables completely imbedded in rubber or enclosed between one or more fabric plies are used for very high tensile loadings that are beyond the capacity of the fabric-carcass belts. A more recent development in high tensile strength belts has been the use of Kevlar (DuPont), high strength aramid fibers in woven, cord, solid woven, or cable construction. A comprehensive survey of carcass constructions used in conveyor belt technology is available (16).

2.1.4. Take-Ups

A take-up is required on a belt conveyor to ensure the proper belt tension at the drive pulley and along the conveyor, as well as to ensure the proper troughing contour between idlers. A take-up is also needed to compensate for changes in belt length caused by elastic stretch during start-up, and any elongation characteristics of the belt that occur over a period of time.

Manually adjusted screw or ratchet take-ups that adjust the position of the tail pulley to control belt tension can be used on relatively short, light duty conveyors. Automatic take-ups are used on conveyors over about 25 to 30 m long. The most common is the weighted automatic gravity take-up (see Fig. 1**a**). Other types of automatic take-ups have hydraulic or pneumatic powered devices to adjust a snub pulley position and maintain a constant belt tension. The required take-up movement varies according to the characteristics of the belt construction and the belt length. Typically, take-up movements for plied belts are 2% to 3% of the center distance between head and tail pulley, and about 0.5% for steel cable belts. The take-up movements required for solid woven belts are usually shorter because of the lower elastic stretch. Take-up requirements for a particular situation should be confirmed by the belt manufacturer.

2.1.5. Backstops

A backstop is a device that permits rotation of the pulley in the forward direction but automatically prevents rotation in the opposite direction. A backstop should be installed at the headshaft of an inclined belt to prevent the belt from moving in reverse if the power to the motor is interrupted or if there is a failure in the mechanical drive system.

2.1.6. Belt Cleaning

Idlers and snub pulleys on the return run support the belt on the material carrying surface of the belt and, therefore, are exposed to any material that may cling to the surface of the belt. This material is then transferred to the surface of the return idler rolls and snub pulleys and can adversely affect the training and control of the belt path. Cleaning sticky materials from the surface of a belt is difficult. There are available a variety of single and multiple-blade belt scrapers having spring or counterweighted supports, motor driven or belt powered

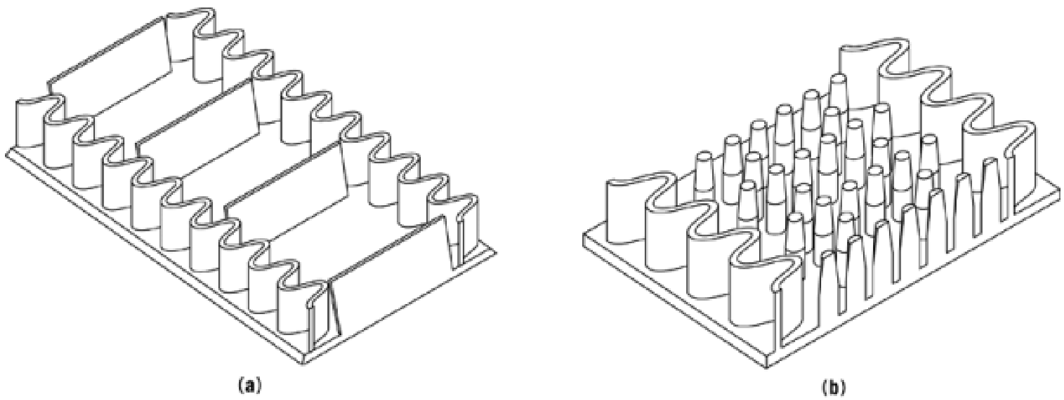

Fig. 2. (**a**) Flexible-wall belt (16, 17); (**b**) Cambelt.

blade, or brush cleaners. Each has had varying success in thoroughly cleaning the belt surface. A variety of self-cleaning idlers constructed using rubber-disk, spiral, and beater rolls for use on the belt return run have been moderately successful in dislodging material from the belt surface.

2.1.7. Power

The power required to drive a belt conveyor is derived from the tensile forces required to propel or restrain the belt at the design speed. These include the tensile forces produced by the frictional resistance of the drive, conveyor components, and material; the acceleration of the material; and the gravitational forces required to lift or lower the material. Detailed information and methods of calculation can be found in belt conveyor design handbooks and in Reference 9.

2.1.8. Newer Designs

A number of belt conveyor designs that depart from troughed belt technology have come onto the market since the mid-1980s. These are expected to have a significant impact on belt conveying technology.

2.1.8.1. Flexible Sidewall Belt Conveyors. The flexible sidewall belt consists of three elements: a flat cross-rigid base belt, accordion-pleated flexible side walls to restrain the material being conveyed, and a cleat or divider spaced at intervals along the belt to prevent slideback of the material when the belt travels on an incline as shown in Figure 2**a**. The flexible sidewall allows the belt to pass around head and tail pulleys and bends on the vertical plane, so that it may be loaded and discharged on horizontal runs. The bend from horizontal to the elevating slope angle is achieved by means of deflection wheels that control the upturn of the belt. Sidewall heights range from 40 to 400 mm. Conveyor slope angles up to 90°, lift heights of 80 m, and capacities up to 10,000 t/h have been attained using these conveyors (16, 17). Another version of the flexible wall belt is the Camflex belt (Fig. 2**b**) which combines a flexible side wall with knobs projecting from the belt surface to provide frictional drag on the material to permit conveying at steep inclines.

2.1.8.2. Serpentix Three-Dimensional Continuous Path Conveyor. The Serpentix conveyor (18), consists of a combination of conveyor track and belt guidance system. Convoluted belt pan modules are sequentially fastened together to form a continuous belting surface. The convolutions, which enable the belting surface to follow horizontal, vertical, and helical paths, also act as a cleat, permitting transport of loads at steep inclines. The convoluted belt is opened and flattened at the discharge, thus enabling cohesive or adhesive materials to be scraped from the belting surface. The modules are supported on a strand (or strands) of guided roller chain or drag chain, which provides the pulling element for moving the conveyor in a continuous path. These

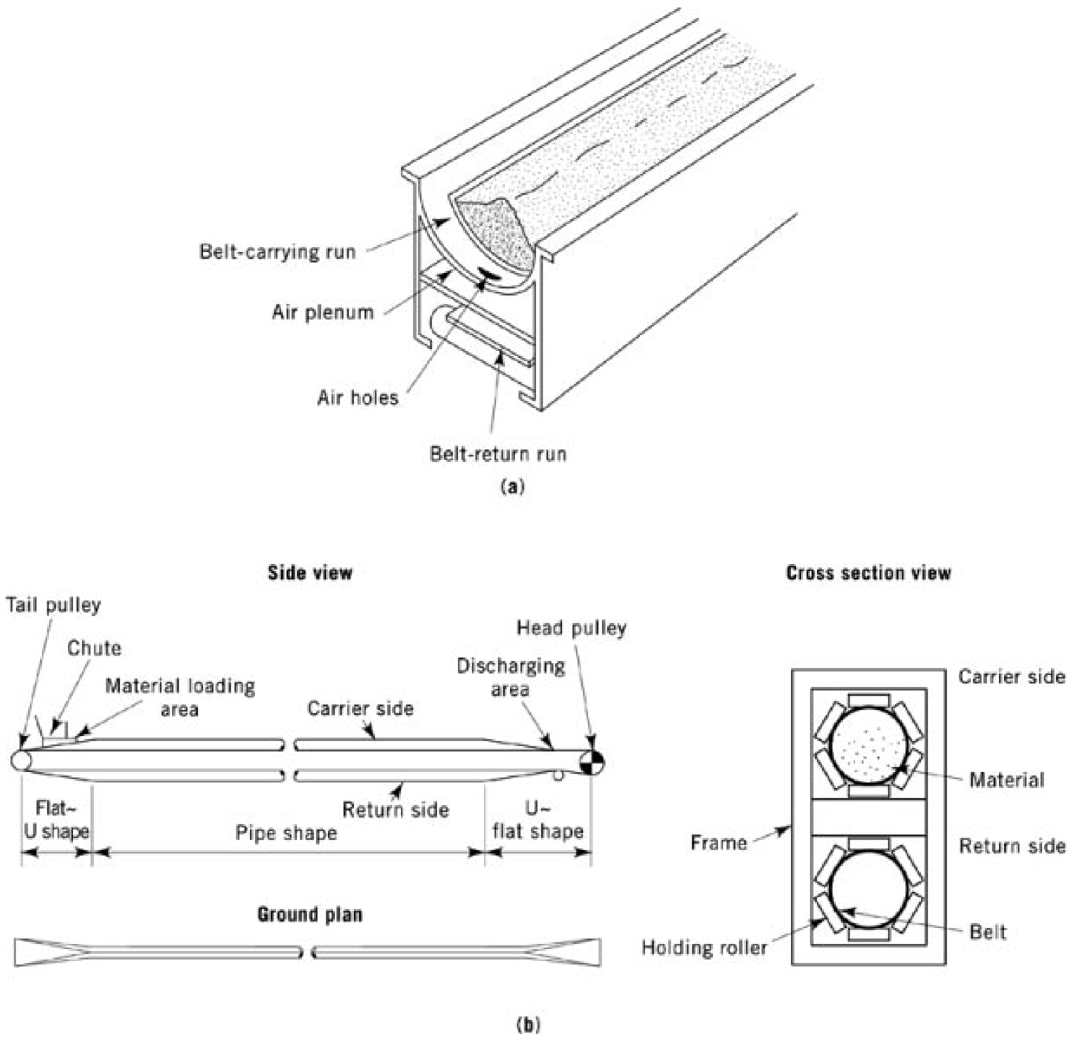

Fig. 3. (**a**) Air cushion-supported belt conveyor; (**b**) the Japan Pipe Conveyor.

conveyors have been used for handling a wide variety of wet and dry bulk materials and industrial waste since the early 1980s.

2.1.8.3. Air Cushion Conveyors. Figure 3**a** shows an air cushion-supported belt conveyor. The belt and material are supported on an air film created by passing air through small holes or slots in a U-shaped trough beneath the belt. The air film reduces the conveying friction losses, resulting in a reduction in required power and in belt wear as compared to idler supported belts. Belt widths range up 900 mm and transport distances up to about 90 m.

2.1.8.4. Sandwich Belt Conveyors. The sandwich belt conveyor employs two rubber belts that sandwich the conveyed material between them, enabling the conveyor to transport material at inclines up to 90° from the horizontal. These conveyors have been operating in self-unloading bulk cargo carriers on the Great Lakes since the 1960s (19). They are now being designed and put in service for land-based conveying. There are two general types of designs: one uses a cover belt over a troughed belt (20), and the other two flat belts with the edges pinched together to restrain the material while moving it in the inclined or vertical lift section. Material is loaded on to these belts at a horizontal run before the incline, and discharged after the incline. Belt widths range from 900 mm to 1380 mm. The sandwich belts have been used for conveying at inclines ranging from 30 to 90°, at rates up to 400 t/h.

2.1.8.5. Enclosed Tubular-Type Belt Conveyors. Manufacturers have been working to develop a belt that can totally enclose the material to be conveyed. This would minimize spillage and dust release into the environment, and would eliminate the need for cleaning the belt surface. Several designs have reached the commercial stage and have been installed in industrial plants. A review is available (21).

In the pipe conveyor, patented by the Japan Pipe Conveyor Company, the belt is in a flat position as it passes over the tail pulley to be loaded. It then passes through a transition section where it is transformed into a tubular shape with the belt edges overlapping to form a seal. The belt is constrained in this position by special multiroll idlers, spaced at intervals along the length of the conveyor. The belt is opened at the head pulley to discharge the material, and then reformed into the tube-shape as it continues back on the return run. The tubular belt configuration encloses the material, and thereby eliminates the need for weather and dust enclosures used on conventional belt conveyors. A further advantage is that the material handling surface of the belt never touches the idler surfaces, thereby eliminating the problem of return idler contamination. The diameter of the pipes formed by the belt range from 100 to 900 mm. An example is shown in Figure 3**b**.

The pipe conveyor can convey materials at higher angles of inclination than conventional trough belts and can be directed through very long radius curves in both vertical and horizontal planes. These features help to make it more competitive with conventional trough belts in those situations where a multiplane path using conventional belts would require using multiple belts and transfer points.

The belt is specially designed for this application. The compounding of the elastomer covers are controlled to reduce the pipe closing resistance and the plies in the carcass are stepped back at the edges to reduce edge stiffness and enhance the sealing when the belt is overlapped. The Rollgurt-Conveyor (22) is a similar type of enclosed tubular belt conveying system that was installed in an industrial plant in Sweden in 1990.

2.1.8.6. Folding Belt Designs. In folding belt conveyors, the belt edges are folded over the top of the material after it has been loaded on to the belt. The Goodyear folding conveyor belt carries material on conventional troughing idlers. The belt is specially constructed so the sides can be folded over the top of the material and constrained by guide rollers to enclose the material during transport over the troughing rollers. The U-Con belt conveyor (23) folds the belt and transports material over flat rollers.

2.1.8.7. Enclosed Pocket Belt Conveyor. The Sicon enclosed belt conveyor, shown in Figure 4, uses a special flat belt having flanged, cable-reinforced edges. After filling, the belt passes through a transition section where it is folded into the shape of a hanging pocket with both flanged edges pressed together by pinch rolls mounted at intervals on an overhead frame. The belt, having its edges constrained by the pinch rolls, and the material enclosed in the pocket, are transported along a path of guide and support rollers on an overhead frame. The path can include vertical and horizontal turns. The belt is opened at the head pulley to discharge the material and then reformed into the pocket shape for the return run.

2.2. Screw Conveyors

A screw conveyor consists of a helical flight fastened around a pipe or solid shaft, mounted within a tubular-shaped or U-shaped trough. As the screw rotates, material heaps up in front of the advancing flight and is pushed through the trough. Particles in the heap, adjacent to the flight surface, are carried part way up the flight surface and then cascade down on the forward-moving side of the heap. Screw conveyors are of simple, relatively low cost construction, and are comprised of highly standardized component parts. These conveyors can handle a wide variety of solid particles ranging from lumps to powders within a completely enclosed housing at temperatures up to 275°C or higher if they are liquid cooled. The flights can be configured for particle mixing during transport, and flights and housing configured for particle cooling. Lumpy, sticky, or fiberous materials

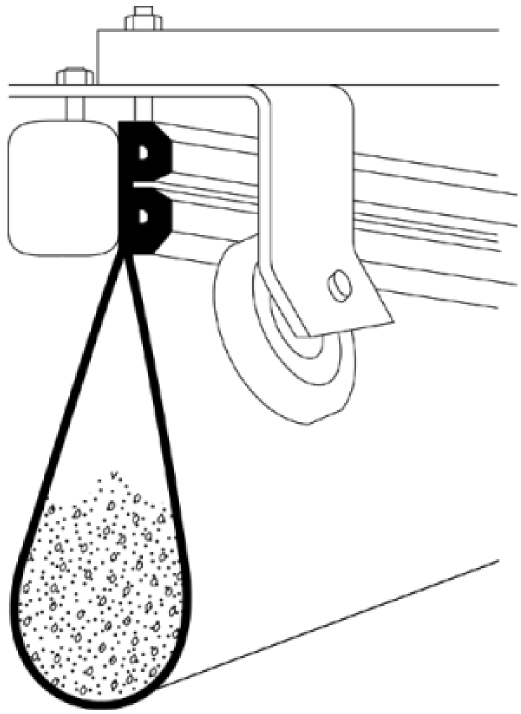

Fig. 4. The Sicon belt conveyor (22).

may cause problems in a screw conveyor. Conveying distances are limited by the torque capacity of available drive shafts. Power requirements are relatively high and conveying efficiency is considerably reduced when screws are inclined or mounted vertically.

2.2.1. Construction

The parts, dimensions, and dimensional tolerances used in manufacturing of screw conveyors are highly standardized. Standards for dimensions and minimum service requirements are available (24–26). These are accepted by most of the industry.

In a typical screw assembly, the flights are fabricated, then welded to a pipe that has bushings press-fitted or welded into each end to provide reinforcing for the conveyor couplings. There are two types of flights: helicoid and sectional.

Helicoid flights are formed by rolling a strip of metal so that one edge is compressed to half its original thickness, causing the strip to form a continuous helicoid having a uniform pitch. When this flight is mounted on the pipe shaft, the thinner edge is at the outside circumference. Helicoid flight conveyors are commonly fabricated in diameters up to 460 mm.

Sectional flights are formed by cutting a ring from a plate, making a radial cut in the ring, and cold pressing it in a die to form a single flight pitch (25). The flight thickness is the same at the outer and inner edges. The individual pitches are slipped onto the pipe shaft and butt welded to each other and to the pipe shaft. Sectional flight conveyors are commonly manufactured in diameters up to 600 mm. A sectional flight, which is more costly than a helicoid one, is used where the thicker flight edge can be used to advantage: it provides a longer service life when handling abrasive materials and additional strength to resist stresses caused when

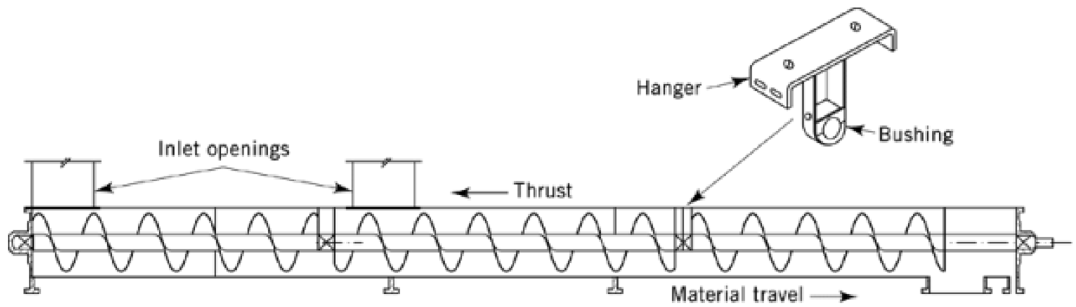

Fig. 5. A screw conveyor assembly.

handling lumpy or compacting materials. Because each flight is made individually, the sectional flight screw is also used where varying or special pitch screws are required.

Screw conveyors are assembled by connecting screw sections in sequence within a trough enclosure, using screwed, flanged, or bolted connections. The most commonly used is the bolted connection using two special bolts spaced 90° apart, and inserted through the pipe, collar, and coupling shaft. The screw sections are supported at intervals within the trough by bushed hangers. The bushings, installed around the exposed portion of the coupling shafts between adjacent screw sections, are supported in the hangers that are fastened to the trough. Standard hanger spacing is from 3.45 to 4 m to match the standard screw lengths. The hanger bushings are exposed to abrasive wear from the material being transported, and must be replaced periodically. Hangers and bushings are an obstruction to flow and bushings are subject to wear; thus there are advantages to minimizing or eliminating hangers. This is often done by increasing the spacing between hangers, and using over-sized, larger diameter shafts to resist the increased bending stress. A typical screw conveyor assembly is shown in Figure 5.

2.2.2. Considerations for Sizing

2.2.2.1. Lump Size. The amount, size, and character of lumps in the material to be handled is the first consideration when selecting the proper diameter of a screw for a particular application. If the lumps are expected to be friable, and easily broken in passing through the conveyor, or if the material contains no lumps, there is no limitation on the diameter of the conveyor, and selection can be made on conveying capacity alone. If the lumps are hard and not liable to be broken up during transit through the conveyor, then the screw diameter must have enough clearance between the pipe shaft and trough to accommodate these lumps. Manufacturers usually select the minimum screw diameter on the basis of maximum lump size and the percentage of those lumps in the material to be handled. CEMA recommendations (24) regarding acceptable percentages of lumps in mixtures of particles to be handled in screw conveyors is followed by most manufacturers.

2.2.2.2. Material Characteristics. In general, screw conveyors can handle all free-flowing materials. The more free-flowing, the lower the energy required to transport the material. Cohesive materials and materials that tend to pack in the radial clearance between the flight tip and the trough require special considerations. These could include such things as closer than standard flight to trough clearances, tapered or wear-resistant flight tip surfaces, special nonsticking surfaces or materials on the flight, special flight geometries, and larger drives. The higher the filling (loading) in a trough, the more contact there is between material and the hanger and bushing. To assure a reasonable service life for the bushings and the coupling shafts that run in these bushings, the conveying industry has established a guide for determining the maximum depth of material that should be carried in a screw trough for particular materials.

Standard practice calls for limiting the depth of loading in a trough where hangers are used to 45% of the cross-sectional flow area when handling very free-flowing fine or granular, nonabrasive materials, 30% for less free-flowing materials and for moderately abrasive materials, and 15% for very abrasive materials. The reason for the limitation on cross-sectional loading is to avoid jamming material around the hanger and to achieve a reasonable service life for the bushings and flights. However, if there are no hangers in the conveyor, trough loadings up to 90% are possible. The loose bulk density for a material is used for calculating actual cross-sectional loading in a screw conveyor. The actual bulk density of material as it is exposed to agitation as it moves through a screw conveyor can only be estimated from loose densities determined by bench-top tests.

2.2.2.3. Flight Geometry. The flight pitch effects screw conveying efficiency. A pitch-to-diameter ratio of one has been found to provide the best combination of efficiency and cost effectiveness for horizontal screw conveyors. Standard screws, therefore, have a pitch equal to the diameter. There are a number of other flight configurations used for special purposes that include feeding, mixing, gas stripping, and preventing flushing. A description of these, and others, can be found in the literature (24). Information on screw conveyors is also available (27–29)

2.2.2.4. Screw Inclination. The angle at which the screw is inclined to the horizontal affects conveying efficiency. As a screw is inclined, the slope of the flight surface becomes closer to horizontal and becomes less effective in moving material forward. At some point, depending on the material properties and the conveyor geometry, the increased turbulence and tumbling of the material causes a portion of the material to spill back over the pipe and over the flight tips into the preceding pitches. This reduces the conveying efficiency and increases the cross-sectional loading. Higher speeds and additional power are then required to achieve capacities comparable to a horizontal screw. As a general rule when the angle of inclination exceeds 10 to 15°, modified designs are required in order to offset the reduction in conveying efficiency. These modifications can include close clearances between the flight and trough, a shorter screw pitch, a tubular housing in place of a U-trough, and increased screw speed. Information on design of inclined screws can be found in Reference 24.

2.2.3. Vertical Screw Conveyors

Many free-flowing materials can be conveyed vertically with a screw. Screw elevators, designed for this purpose, have tubular housings, run at speeds ranging from 200 to 400 rpm, and have volumetric efficiencies of about 25% of an equivalent horizontal screw. Most of these machines are limited to vertical lifts of about 9 m, although some units have been built for lifts up to 30 m for handling grain and other agricultural materials. The vertical screws are not self-cleaning; ie, if material feed to the inlet at the bottom stops, even though the vertical screw is rotating, some material remains at the bottom until more material is fed into it.

2.2.4. Screw Conveyor Capacity

The volumetric capacity of a horizontal screw conveyor is calculated on the assumption that all material contained within one screw pitch moves one pitch distance in one screw revolution. Volumetric conveying capacity is calculated as

$$\text{volumetric capacity} = \left(A_s - A_p\right) P{\cdot}K{\cdot}N$$

where A_s is the cross-sectional area of the screw flight, A_p is the cross-sectional area of the pipe shaft, P is the flight pitch, N, the rotational speed, and K is the percentage of the cross-sectional annular space between flight and pipe shaft occupied by the material. $K = 0.45$ for fine to granular, free-flowing, nonabrasive to mildly abrasive particles; $K = 0.30$ for fine to small lumps, average flowability, mildly abrasive particles; and $K = 0.15$ for very abrasive materials. This procedure ignores the volume occupied by the flight itself, but is sufficiently accurate for most engineering purposes.

2.2.5. Power to Operate a Screw Conveyor

The power required to operate a screw conveyor is dependent, to a large extent, on the handling characteristics of the material to be transported. Formulas for calculating power use empirically derived factors to account for the conveying characteristics of specific materials, the configuration of the screw, and the bearing friction. These formulas have been developed by CEMA and can be found in the literature (24, 25) and in engineering handbooks. It is assumed that the total power is equal to the sum of the power required to overcome friction and the power required to transport the material.

2.3. Bucket Elevators

In a bucket elevator, a series of buckets attached to an endless belt or chain are filled with material and lifted vertically to a head pulley or sprocket, where the material is dumped. The buckets are then returned back down to a tail pulley or sprocket at the bottom. Bucket elevators are not self-feeding. They must be fed at a controlled rate to avoid overfilling the buckets and damaging the machinery. In the usual arrangement of a bucket elevator, the chain or belt path is vertical or steeply inclined in a single plane. Special chain supported bucket systems that can travel in two and three planes have been developed.

There are four broad classifications of bucket elevators: centrifugal, continuous, positive, and internal discharge. Centrifugal and continuous discharge elevators are by far the most commonly used. Two specialized versions used for high capacity handling are the super-capacity elevator and the cement mill elevator. The positive discharge and the internal discharge elevators are used for special applications. The various elevator types are shown in Figure 6.

2.3.1. Centrifugal Discharge

In centrifugal discharge elevators, the buckets are spaced apart on the chain or belt. Material is scooped from the boot and then discharged by centrifugal force as the buckets approach and pass over the head pulley or sprocket. Speed of the chain or belt is critical to proper discharge of the material. The critical speed has been defined as the speed at the point where the centrifugal force at the center of mass of the material in the bucket is equal to the gravitational force (30). The best operating point for an elevator is where the centrifugal force is two-thirds the gravitational force. The effects of bucket geometry and speed on material discharge have also been reported (31, 32). Changes in exit trajectory of the material leaving the bucket as a result of material friction on the bucket wall and the change in center of gravity of the mass as it slides along the wall have been investigated.

Industrial, centrifugal elevators usually operate at speeds of about 75 m/min, and handle free-flowing, fine and loose materials having lump sizes of ≤ 50 mm. Sticky material can be a problem. Fine fluidizing materials often require perforations in the bottom of the buckets to vent entrapped air. Centrifugal elevator capacities range up to 370 m^3/h for a single row of buckets, and up to 1400 m^3/h for multiple rows of buckets. The buckets can be mounted on a belt or chain.

2.3.2. Continuous Discharge

Buckets are mounted end-to-end on the chain or belt in continuous discharge elevators forming a continuous strand. Material is fed through an inlet chute into the rising buckets as they pass through a loading leg. The loading leg is formed of fixed vertical plates mounted within the boot, in close proximity to each side of the rising buckets, to confine and direct the material stream. The material, which discharges by gravity as the bucket passes over the head pulley or sprocket, slides over the inner surface of the bucket, out over the back of the bucket immediately ahead, where the trajectory carries it out through the elevator discharge spout. The back of each bucket is fashioned with projecting sides that form a chute to contain the flowing material from the preceding bucket.

Continuous elevators can handle a wide range of materials from light to heavy, as well as free-flowing granular and pulverized materials containing lumps up to 100 mm. This elevator handles material more gently than a centrifugal elevator. Bucket speeds range from 30 to 46 m/min. The lower speeds are used in order to

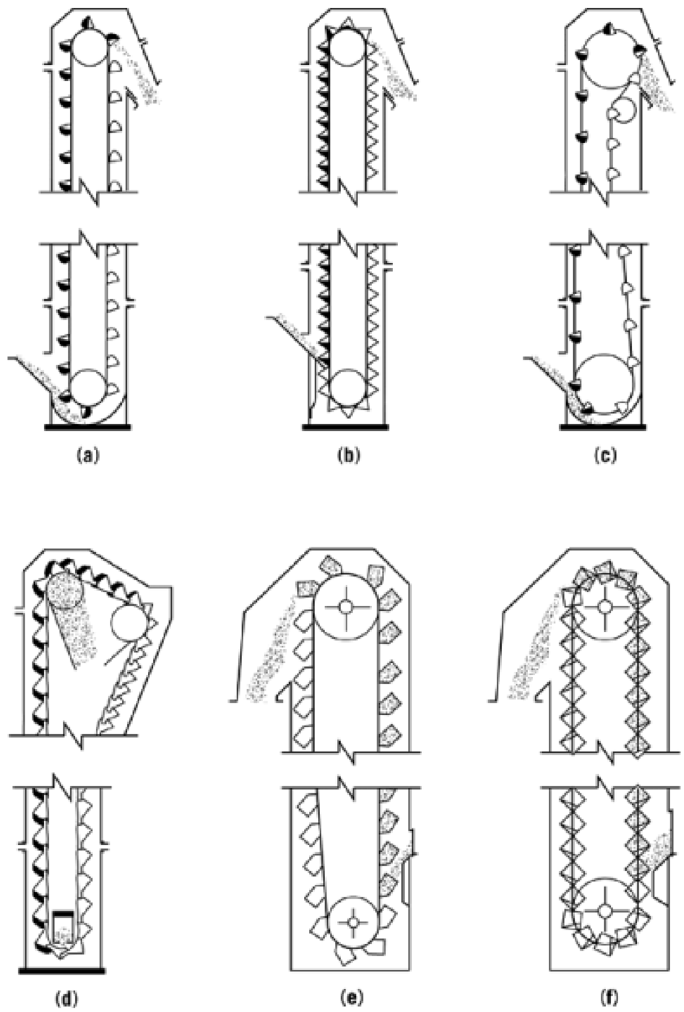

Fig. 6. Bucket elevators: (**a**) centrifugal; (**b**) continuous; (**c**) positive; (**d**) internal discharge; (**e**) super capacity; and (**f**) cement mill.

properly fill the buckets when fluffy, low density materials are handled. Capacities range up to 75 m^3/h on standard elevators.

Super-capacity elevators are continuous type elevators in which the buckets are mounted between two strands of chains. This arrangement makes it possible to handle a larger volume because the bucket can be extended in back of the chain. Elevators of this type are capable of handling up to 375 m^3/h.

Cement mill elevators, also a version of continuous elevators, use a pocket-shaped bucket (Style AC in the U.S.), mounted on a single strand of chain. The buckets can be closely spaced to pick up material fed through a loading leg, or can be more widely spaced to pick up material from the loading leg, as well as scooping from the boot. Although originally developed for cement handling, this elevator is also used for handling very fine, aeratable powders. The bottom of the buckets have air release holes to allow entrained air to escape during filling, thereby increasing filling efficiency. Capacities range up to 210 m^3/h.

2.3.3. *Positive Discharge*

In positive discharge elevators, spaced buckets are mounted between two strands of chain and the buckets are discharged by snubbing the chain after the head sprocket, so that the buckets are inverted over the discharge spout. These elevators are used for handling materials that tend to stick in the buckets or for low density materials that do not discharge readily. Capacities range up to 40 m^3/h.

2.3.4. *Internal Discharge*

Continuously overlapping buckets supported by a strand of chain at each end are inverted as they pass over the head sprockets in internal discharge elevators. Material is loaded into the bucket through a chute extending into the side of the elevator boot section, and is discharged through a chute extending out the side of the head section. This design is useful for gentle handling of small particles such as plastic pellets, granular chemicals, agricultural products such as seeds, shelled nuts, etc., and even mechanical parts. Capacities range up to 23 m^3/h.

2.3.5. *Buckets*

Elevator capacity is a function of bucket volume as well as speed and spacing on the chain or belt. There are a variety of bucket geometries, and selection is based on the materials to be handled. Buckets used in centrifugal discharge elevators are shaped and reinforced so that material may be easily scooped or dug from the boot at the lower end of the elevator where the material enters. Buckets used in continuous elevators are shaped to receive material that flows into them from the inlet chute in the boot. Most of the buckets can be furnished in cast malleable iron, carbon, galvanized and stainless steel, and other corrosion-resistant material. Buckets are also available in cast and injected molded nylon or polyethylene. The polymer buckets weigh substantially less than the metal ones, so the chain or belt loading is reduced when used. These synthetic buckets can be used for fine abrasive materials and in many cases slightly adhesive materials that do not readily release from a metal bucket.

2.3.6. *Casing Enclosure*

Steel casings are normally furnished in intermittently welded, dust-tight construction which is the lowest cost construction. Weather-tight, watertight, or gastight can be specified. Casings can be fabricated of metal or fiberglass. Except for very large units, bucket elevator casings are self-supporting against vertical loads imposed by the buckets, chain, material, and drive. However, the casing must be braced or anchored at appropriate intervals to maintain stability.

2.3.7. *Chain*

Chain, which can be used in all types of elevators, must be used for handling hot ($>120^\circ C$) materials. Several types of chains are commonly used. Selection depends in large part on the abrasiveness and temperature of the material and the required working chain loading (chain pull) for the particular application. The three types of chains most commonly used in industrial elevators are (*1*) steel side bar, bushed chain, or steel knuckle chain made entirely of alloy steel. Hardened steel bushings with flat surfaces on each end are press fitted and locked into similar shaped holes in the side bars, forming a single link. The links are connected together by side bars and hardened pins that pass through the bushings and are locked to prevent rotation. These chains are used for heavy-duty elevator service. (*2*) Welded steel chain which is dimensionally similar to the knuckle chain. Hardened steel barrels are welded between steel side bars and the links are connected by heat treated pins. (*3*) Combination chain is made up of cast malleable iron links alternating with steel side bars. The cast links are joined by hardened steel pins inserted through machined holes in the steel side bar and cored holes in the cast link. The pins are locked against rotation by a machined flat surface on the end of the pin engaging a similar shaped hole in the steel side bar. These chains are commonly used for less severe elevator duty.

2.3.8. Belting

In a belt elevator, the buckets are fastened to the belt with special flat-headed bolts. Belts used for bucket elevator service have the same type of construction as those used on belt conveyors but the selection criteria differs in one important respect: the belt must have sufficient body strength to prevent the bolt heads from pulling through the belt carcass. The carcass must resist the stress on the bolts caused by the digging of the bucket in the boot, and the prying forces caused by material lodging between the belt and the back face of the bucket as the belt bends around the pulleys. In many cases the bolt pull-out rating of the belt determines the selection of the belt construction rather than the working tensile loading. Resistance to bolt pull-out is provided by the appropriate number and thickness of plies as well as the ply material.

Belt tensile strength must withstand the working load that includes weight of the belt, buckets and material suspended on the carrying side, digging and filling loads, friction in the system, and the additional loads required to provide driving friction. Procedures for estimating the digging and friction loads, and bolt pull-out ratings of belts, can be found in elevator or belt manufacturers handbooks.

Elevator belts can be spliced endless by bolting overlapping ends (lap splice); butting the ends then overlapping them with a belt strap, and bolting them together (butt strap splice); connecting butted ends with a bolted hinged plate-type fastener (mechanical fastener); clamping butted ends (clamp fastener); or by overlapping the plies and vulcanizing them together. Lap and butt strap splices are most commonly used.

Head pulleys for belt elevators are crowned to help train and guide the belt and quite often are rubber lagged to increase traction with the belt. Wing-type pulleys, which resemble a squirrel cage, are often used as a tail pulley to minimize any pinching of materials between the belt and tail pulley surface.

2.3.9. Take-Up and Hold-Back

An elevator chain wears and elongates, and a belt stretches during service life. A chain also elongates when handling hot materials. Therefore, a take-up adjustment is needed to maintain tension between the head and foot shafts. A manually adjusted screw take-up that moves the tail shaft or head shaft or a self-adjusting weighted take-up that maintains a constant gravity force on the tail shaft may be used. The gravity take-up must be used when handling hot materials in order to maintain chain and sprocket tooth engagement, as the chain length changes with thermal expansion.

The weight of material in the buckets on the loaded side of an elevator chain causes the elevator to momentarily run backwards if, during operation, the power is interrupted or there is a failure in the driving system. Because this could be a hazard to operating personnel, as well as damage to the elevator, a backstop, similar to that described for a belt conveyor, should be used.

2.4. Vibrating Conveyors

A vibrating conveyor consists of a trough supported by tuned springs and/or hinged links having a drive system. The drive system is arranged to oscillate the trough, causing solid particles to be moved along the trough. Thus these conveyors are sometimes called oscillating conveyors. There are two types of oscillating conveyors: reciprocating and vibrating.

On a reciprocating conveyor, material is carried forward in a horizontal direction by frictional contact with the trough. Inertia causes the material to be left in that position as the trough is quickly returned to the initial position. These conveyors are useful for handling granular free-flowing materials with a minimum of attrition.

On a vibrating conveyor, material moves along the trough in a series of hops. The particles are accelerated from the trough in an upward and forward trajectory as the trough moves forward. The particles return to the trough in the forward position as the trough completes its return stroke. The vibrating conveyor is the most commonly used type of oscillating conveyor because of its flexibility and ability to handle a wide range of materials.

Material must be fed onto a vibrating conveyor at a controlled rate. These conveyors are not designed to operate under a head load from solids in a storage silo or hopper. In addition to horizontal conveying, these conveyors can be used to perform other functions such as elevating, heating, drying, cooling, fluidizing, agglomeration, screening, and dewatering (qv).

Vibratory conveyors are capable of handling a wide range of materials. They provide gentle handling of food products such as friable flakes and pellets, pharmaceuticals, powdered and granular chemicals and minerals, and discrete metal parts. They are uniquely suited for handling abrasive, hot, and dusty materials and can be designed to withstand heavy impact loads from materials such as rocks, iron and steel castings, and metal and wood scrap. They operate at frequencies ranging from 5 to 15 Hz; strokes range from 50 to 5 mm; and lengths are up to 50 m.

2.4.1. Material Handling and Capacity Considerations

Dry granular material is almost always easily handled on a vibratory conveyor. Many fine powders and pulverized materials move more slowly on a vibrating trough and these tend to deaerate and form a relatively impermeable, slowly moving layer when exposed to the vibration. As a result, these types of materials can only be transported in relatively shallow layers on the trough. Wet, fine materials or adhesive materials do not move well on a vibrating trough. Methods used to improve flow along the trough include: heating the trough, lining the trough with an elastic polymeric material, or using a very long stroke on the pan oscillation.

Linear transport velocity of the material is almost proportional to the product of frequency and stroke for these conveyors. However, the transport velocity and the depth that can be obtained with a specific material is dependent on the handling characteristics of that material. Manufacturers have accumulated data banks relating material characteristics to attainable conveying velocities for their proprietary conveyor designs.

The movement of material on vibrating troughs has been studied and there has been some success in estimating the theoretical velocities of free-flowing granular materials in single array or in thin beds, using empirical material flow factors derived from tests (33). These correlations based on single particle or thin layer trajectories are not representative of real-life, thick bed situations. The complexities involved in predicting the influence of vibration on material, the handling properties of which cannot be well defined, makes it prudent to conduct tests to confirm the design parameters for any vibrating conveyor application.

2.4.2. Drive Systems

Positive, fixed displacement mechanical drives are the most commonly used. These conveyors consist of a trough and a spring system, usually fiber glass or metal, that supports and guides the trough from the rigid base, and a motor driven crank and connecting rod that drives the trough. The rotation of the crank arm produces a fixed trough displacement. The drive system is tuned to operate subresonant, ie, just below resonance or natural frequency with the springs and trough. Much of the energy is alternately stored and released back into the system by the springs. Thus the only power needed is that for starting and for making up for losses resulting from friction and air resistance.

Leaf springs are used for reaction and support on light to medium duty applications. For heavier duty applications, stabilizer links are used for supporting the trough and tuned coil or elastomer springs are used for reaction. Shock absorbing devices are used in the drive train to isolate shock loads developed during starting. The direct mounted rotating eccentric mass design makes use of a rotating exciter, consisting of adjustable-position eccentric weights mounted on the shafts of a double-shafted electric motor, which is mounted directly on the trough or on a counter-balance conveyor base. Because these machines do not have a positive crank arm drive, they do not have a fixed amplitude. This type of conveyor also operates at subresonance and is fine-tuned by weight adjustment on the trough before being put in service. This design requires fewer moving parts than the direct drive machine, but requires more attention to design and tuning. The exciters usually operate at frequencies of 15 to 20 Hz.

Excitation can also be supplied by an electromagnetic exciter that uses a rectified, pulsed a-c power supply, or a-c supply to an apposed electromagnet/permanent magnet drive. These units operate at very short strokes and frequencies of 50 to 60 Hz. Although designed primarily as feeders, they are occasionally used as short conveyors.

Compressed air or hydraulically driven reciprocating piston or rotary exciters are sometimes used in short conveyors. They are particularly useful where explosion hazards limit the use of electrical drives.

2.4.3. Design Variations

Vibrating conveyor troughs can be custom-designed for particular needs. Troughs can be rectangular, with or without covers, and they can be tubular. Tubular troughs are useful where dust-tight operation is required. Inclined flat bottom troughs with a saw-tooth-shaped carrying surface can be used for conveying granular materials up 10 to 20° slopes. Troughs can be provided with multiple discharge openings and can be designed with expansion decks to handle materials at temperatures up to 538°C. Tubular, or rectangular troughs, wound in a vertical spiral, can be used for vertical conveying of granular materials.

2.4.4. Isolation Mounting

The static and dynamic forces that are imposed on a supporting foundation or supporting structure by a vibrating conveyor are an important consideration in conveyor selection. Static forces are vertical forces resulting from the weight of the conveyor assembly and material in the trough. The dynamic forces act in the line of action of the conveyor and can be resolved into vertical and horizontal components. The structures supporting these conveyors must be rigidly designed to withstand cycling forces. The conveyors can be designed to minimize the forces transmitted to the supporting structure. This is particularly desirable when the conveyors are to be mounted on elevated supports, or on the upper floors of a building. Methods to reduce transmission of forces to supporting structures include: hanging the conveyor on flexible cables, mounting the conveyor on a tuned spring supported weighted base, or using a counterbalance mounted on a tuned spring system identical to that on the conveyor trough and driving it 180° out of phase with the trough. The dynamic forces transmitted into supporting structures have been reduced by up to 95% by these methods.

Information with regard to isolation mounting can be found in References (33–37).

2.5. En-Masse Conveyors

An en-masse conveyor consists of an endless chain or cable, pulling a series of spaced skeleton or solid plug flights through an enclosed casing or housing. Material is introduced through an opening in the casing, where it is captured by the flights and drawn through the casing until it reaches an opening in the housing, where it discharges by gravity.

En-masse conveyors offer unique advantages over other types of conveyors: they are compact in cross section and totally enclose the bulk material; they can be made vapor and gas tight; they can handle many materials with little particle attrition; they can have an L-shaped or Z-shaped path, thereby eliminating transfer points that are required by conventional straight line conveyors; they can combine feeding, conveying, and elevating in one machine; and they can have multiple inlet and discharge openings.

2.5.1. Material Characteristics

Performance of an en-masse conveyor is very dependent on the characteristics of the bulk materials handled. This conveyor is best suited for nonabrasive, free-flowing, granular or powder materials. Sticky or smearing materials can build up in the clearance between flight and casing causing a mechanical overload. Particles enter into these conveyors between the flights as they move across the feed opening in the casing. The chain or cable restricts the depth of the opening into which any lumps that may be present must fall. If a lump does not drop completely into the opening before the advancing flight carrying it reaches the enclosed portion of the casing it gets pinched between the flight and casing. The conveyor chain or cable is then exposed to a potentially damaging shock loading. For this reason, the potential maximum lump expected to be present in a material must be made known before the proper size conveyor can be selected. As a rule of thumb, the largest lump to pass into the conveyor should be no larger than one-half the opening between the tension member of the chain or cable and the casing. Very fine powders that aerate readily can also be a problem. It is prudent to test material in an en-masse conveyor in the manufacturer's laboratory if there is no prior experience with the specific material to be handled.

2.5.2. Chain En-Masse Conveyor

The oldest and most well-known en-masse conveyor for heavy-duty service is the skeleton-flighted Redler conveyor. The open skeleton flights are cast carbon steel or stainless steel. Flights are enclosed in rectangular casings; widths range from 127 to 590 mm. Volumetric capacities range from 0.03 to 17 m^3/min and chain speeds from 1.55 to 60 m/min. Typical speeds for some materials are: 9 m/min (fly ash), 12 m/min (coke), 9–18 m/min (granular chemicals), 38 to 46 m/min (grain) and 30–46 m/min (wood chips). These conveyors can be arranged in a L, Z, and loop path, as well as in a horizontal loop or horizontal to inclined path. They can have multiple inlet and discharge points.

Other chain-type en-masse conveyors use flight configurations made up from plates or bars welded to standard forged chain and mounted in a rectangular enclosure.

2.5.3. Tubular En-Masse Conveyors

Lower cost tubular en-masse conveyors for light duty conveying are also available. There are two general types of construction: solid disks connected by chain links or disks connected by a steel cable. The tubular casings (or pipes) range from 50 to 300 mm diameter. Plugs (flights) are nylon or polyurethane and the casings are carbon steel or stainless steel. These units are able to handle sludge as well as dry powders. A specialized type of disk/chain conveyor called the Aeromechanical conveyor operates at 220 m/min to handle dry, free-flowing powders having cable-driven disks operating in 100 to 200 mm diameter tubes. The tubular conveyors can be arranged in paths similar to those of the Redler.

2.5.4. Other Chain-Type Conveyors

A number of driven chain conveyors are used for conveying bulk solids in horizontal or inclined paths. These conveyors are made up of standard mechanical components that can be configured in different ways to perform a particular task. The types most used in the chemical industry include apron, flight, and drag chain conveyors.

Apron conveyors consist of a series of overlapping or interlocking pans on which material is carried. The pans can have a variety of shapes to fit the required service. The sides are usually extended to contain the conveyed material. The pans are supported on bushed or antifriction bearing shafts and rollers, or flanged wheels, which operate on a track. These conveyors can handle materials over horizontal, inclined, or a combination of horizontal and inclined paths. They handle practically any bulk material including ores, gravel, coal, bulk chemicals, scrap, and refuse materials. An apron conveyor is ideally suited for handling heavy, lumpy and abrasive materials that would be unsuitable for a belt conveyor. Fine material dribbles between the overlapping pans. Apron widths range up to 1600 mm in width and conveyor speeds run up to 19 m/min.

A flight conveyor consists of one or two endless power driven chains carrying spaced scrapers or flights for pushing material along a stationary trough. Discharge can be at the end of the trough or at intermediate points. These conveyors can be arranged horizontally or at an incline. They can handle granular, lumpy, abrasive materials, as well as nonabrasive powders, in concrete, steel, and wear-plate-lined or T-bar-lined, troughs. They can be designed to handle hot materials up to 1000°C using air or water cooled troughs or water submerged troughs.

A drag chain conveyor consists of a single strand of endless cast or welded steel chain that pushes or drags material through a trough. It is a simple, low cost conveyor for handling ash, coal, hot clinkers, and scrap waste materials. A variety of cast iron, cast steel, and welded steel chains are used for these conveyors.

2.6. Air Activated Gravity Conveyor

The air activated gravity conveyor is a very simple, inexpensive, maintenance-free, and low power-using device for conveying fine, easily fluidized, and aerateable powders. Originally developed as the Air Slide conveyor, it consists of a downward-sloped rectangular trough bisected by a porous membrane that defines a lower and upper channel in the trough. When air is supplied to the lower channel, it permeates through the membrane, and aerates powder resting in the upper channel, causing the powder to flow like a liquid down the surface of the inclined membrane. Powder flow occurs even if the membrane is only partially covered with material, because the pressure drop through the membrane is such that the air flow is uniformly distributed across the membrane surface independent of the depth of material above.

There are two types of these conveyors: closed and open. In the closed, the air and powder flow channels are enclosed within the trough. The air that permeates through the membrane exits with the powder in the upper channel. Enclosed types are used for transporting powders from point to point. Open-type air activated conveyors are mounted at the bottom of silos and hoppers to act as flow promotion devices. The upper (powder) flow channel is omitted. When air permeates through the membrane and the surrounding powder, the air causes the powder to flow towards the silo outlet. Multiple, open-type units can be arranged in a variety of configurations and they can be activated in a predetermined sequence to control the powder withdrawal pattern within the silo. Trough widths in commercial conveyors range from 100 mm to 850 mm. Nominal capacities for these widths range from 13 to 1500 m^3/h.

The membrane is usually made from one of several materials. Woven polyester or cotton, the most commonly used and least expensive material, is adequate for temperatures up to 150°C. Sintered plastic is used where a low cost, washable surface is desired. This material is temperature limited by the polymer material to about 60°C and the flow of some powders may cause a static charge build-up on the membrane that could be hazardous in some operations. Woven fiberglass fabric or porous ceramic block is used for temperatures up to about 425°C. Sintered stainless steel powder or bonded stainless mesh is used for corrosion resistance, and for temperatures up to 530 to 650°C. Additional information can be found in the literature (38, 39).

2.7. Pneumatic Conveyors

In a pneumatic conveyor, bulk solids particles are transported through a closed duct in a gas stream. A wide range of particle sizes, from powders to large chunks and from fibersto chopped sheet waste, can be handled through these systems. The only significant restrictions are that the conveying pipe should be able to accommodate the largest particles, and the material should not be sticky. Pneumatic conveyors have a number of important advantages over mechanical conveyors that have led to widespread use: they provide great flexibility and compactness in system arrangement; they can be arranged with a multiplicity of solids pick-up and discharge points; they can provide a complete enclosure for protection from contamination of the operating areas, or contamination of the materials being handled; and they can be designed to provide heating, cooling, drying, or mixing during transport. Recirculating inert gases can be used for safely conveying explosive, toxic, or other sensitive materials.

Disadvantages are more power is required to operate a pneumatic conveyor, compared to a mechanical conveyor for the same capacity and transport path; they are limited to about 50 t/hr capacity in industrial nonagricultural applications; the conveying pipe, bends, and fittings are subject to erosive wear when handling abrasive materials, and friable materials may be damaged during conveying; the pneumatic conveying process is more sensitive to the characteristics of the material to be handled than are most mechanical conveyors. The handling characteristics must be known before a conveying system can be designed. If no prior experience with a particular material in question is available, testing of that material in a pneumatic conveying rig is mandatory in order to produce reliable design data.

2.7.1. Classifications

Pneumatic conveyors are commonly classified as being either a dilute phase, or a dense phase conveyor. The differences between the two can be illustrated by the use of a typical phase diagram (40) to characterize the flow conditions that occur during the conveying process. A typical phase diagram for horizontal conveying is shown in Figure 7, where the pressure drop per unit length of pipe, $\Delta P/L$, is plotted against the average superficial air velocity in the pipe. Line AB represents the pressure drop with air alone flowing $G_0 = O$). When solids are introduced into the conveying line at a constant rate, G_1, the pressure at Point B_1 increases to point C_1, because of the increase in gas/particle drag. If the gas velocity is then reduced, without changing the solids mass feed rate, the solids velocity decreases, the solids loading (mass solids/mass air) therefore increases, and the unit pressure drop follows the path C–D. At point C, the particles are fairly dispersed in a suspension across the pipe cross section, but as the gas velocity is lowered to approach point D, the solid concentration in the moving stream begins to become more concentrated near the bottom of the pipe, and eventually takes on the appearance of a moving rope or strand. As the air velocity is further reduced, a point of minimum pressure, Point D, is eventually reached and at that point, particles begin to settle or salt out along the bottom of the pipe. The air velocity at that point is called the saltation velocity for that specific material in that specific pipe diameter. It has been reported (41) that powders begin to settle just before the minimum pressure point has been reached, whereas large granular particles begin to settle at the point of minimum pressure.

If the pressure conditions at higher solids mass flow rates (G_2, G_3) are superimposed on the phase diagram, the minimum gas velocity required to maintain conveying increases as the solids loading is increased. A line drawn through the minimum pressure points on the phase diagram defines the boundary conditions between what is commonly called dilute phase, to the right of the line, and dense phase conveying, to the left of the line. For a specific material the minimum velocity to maintain conveying increases as the pipe diameter is increased. An intermediate phase between dense and dilute has also been defined to be that condition existing at, or near, saltation conditions, where strands are observed. This definition has not been universally accepted.

A phase diagram for vertical conveying can be constructed in a manner similar to the horizontal phase diagram. The minimum superficial air velocity in a vertical pipe, analogous to the saltation velocity, is called the choking velocity. The minimum air velocity for avoiding choking in a vertical pipe is lower than that required to avoid saltation in horizontal pipes. Because conveyors are usually composed of horizontal and vertical sections, the minimum air velocities used for design of conveying systems are those velocities necessary to avoid saltation in the horizontal sections.

The phase diagrams have been traditionally drawn from actual test data using the average gas velocity measured over a unit length of pipe as the abscissa. Because the gas is compressible, conditions are constantly changing throughout the entire length of the conveying line. In order to more correctly represent these conditions, a normalized phase diagram, where the dynamic pressure term is substituted for the velocity in the abscissa has been proposed (41).

A number of correlations for predicting saltation velocities in gas–solids flow appear in the literature, but apply only to a specific material and the specific conveying conditions under which they were measured (42). No general correlation has been found. All conveyor designers resort to testing to determine saltation velocities and conveying behavior. These data are then scaled to industrial size systems, using geometric and dynamic parameters that are based on experience.

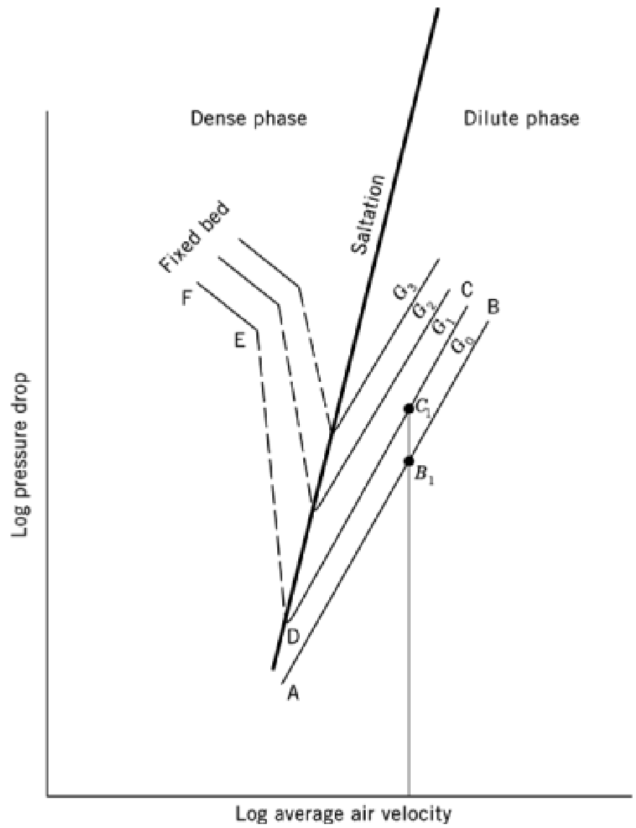

Fig. 7. Phase or state diagram for horizontal conveying where G_i represents a particular mass flow rate, line AB corresponds to the pressure drop for air alone flowing in the system, $G_0=0$, and (—) is the minimum pressure line where saturation occurs. Other points are explained in text.

2.7.2. Dilute Phase Conveying

Dilute conveying systems, sometimes called disperse conveying or stream conveying, operate as positive pressure systems at pressures up to 100 kPa (14.5 psig), or as negative pressure systems (vacuum conveying) at pressures up to -50 kPa (-500 mbar).

Calculation of the pressure drop in pneumatic conveyors is dependent on the use of experimentally derived correlations. Some success has been achieved in modeling the flow of well-dispersed, gas–solids mixtures, but these types of flow streams are not representative of most industrial pneumatic conveying situations. In an industrial plant, the most cost-effective design is one in which the solids are conveyed at the lowest velocity and highest solids loading consistent with maintaining a continuous, nonplugging stream. Under these conditions, the solids stream concentration is highest along the lower part of the horizontal pipes. This concentration changes throughout the length of the pipe, as solids are accelerated after the solids inlet, retarded then reaccelerated at bends in the pipe, and accelerated as the gas expands towards the terminal end of the conveying line. The gas/particle interactions in these nonhomogeneous flows have proven to be too complex to yield a reliable general correlation for calculating pressures, based on theory alone. Information on the application of two phase flow theory to pneumatic conveying design can be found in Reference 41.

2.7.3. Dense Phase Conveying

Dense phase conveying is often called high pressure conveying, or low velocity conveying. The term low velocity conveying is quite descriptive. The velocity/pressure conditions that occur during dense phase conveying are shown in Figure 7. If the gas velocity is reduced below point D, the saltation velocity, the concentration of solids along the bottom of the pipe increases, reducing the gas flow area, causing a sudden increase in pressure and the onset of unstable flow conditions. Assuming the necessary pressure is available from the air source to continue to operate the system, the pressure follows the path D–E–F.

The mode of flow within the pipe is very sensitive to the characteristics of the material being conveyed. Materials that are permeable to air, eg, granular particles having a narrow particle size distribution, can move as naturally forming dunes or long plugs; materials that remain aerated for long periods of time can be transported as a moving bed; fine powders may form unstable moving beds that can become suddenly swept up and transformed into impermeable plugs that block the conveying pipe (43). For these reasons, the design and control of a dense phase conveying system requires close attention to the material handling characteristics. In many cases the individual systems are designed by the manufacturers to operate most efficiently when handling materials that exhibit specific flow characteristics. This is in contrast to dilute phase systems where a wider range of material characteristics can be accommodated by a single design arrangement.

Dense phase systems have been used to transport up to 50 t/h. Although some very long systems up to 600 m have been reported, average systems range from about 150–300 m in length. Advantages over dilute phase systems are: low velocity resulting in more gentle handling of some materials; material can be conveyed over longer distances; the air requirements are less; and these conveyors are generally more energy efficient. Because less conveying air is used, smaller, less costly air/solids separation and dust collection equipment are needed.

Dense phase systems are at cost disadvantage when multiple feed points are required, or when incremental compressed air for conveying is not available from existing sources. In the latter instance, the entire investment cost of an air compressor and associated auxiliaries must be allocated to the cost of the conveying system.

2.7.3.1. System Arrangements. Batch pressure tanks often called blow cases or pressure transporters, are commonly used to feed materials into dense phase conveying systems. These tanks have the capability to seal against the 100–800 kPa (1–8 bar) operating pressures required to operate these systems. Using a single tank feeder, the flow into the conveyor line is intermittent, as the control system cycles the tank operating sequence to fill, seal, pressurize, discharge, depressurize, and refill. Continuous flow can be achieved by using dual tank feeders operating on alternating discharge cycles.

Proprietary designs for rotary valve feeders (star valves) capable of continuous feeding of certain pelleted and granular materials into low velocity, dense phase systems, having system pressures up to 200 kPa (2 bars) have been developed.

Research and experimentation into the flow behavior of powders and granular materials have resulted in a number of commercial designs that can be customized to match the specific flow properties of the material, and can convey at controlled velocities and minimum plugging of the transport lines. Design improvements introduced include provision of means to introduce controlled amounts of air at appropriate points in the transport line, as well as the feed tank vessel, and introducing the air at timed (pulsed) intervals. These improvements have led to better control of conveying velocities, better control of dune and plug formation in the conveying lines with significant reduction in conveying line pluggages, reduced particle attrition, and reduced abrasive wear of the conveying line and fittings.

As in dilute phase conveying, very little published information on estimating pressure drop in dense phase conveyors is available. Industrial systems are designed in most part from scale-up of proprietary laboratory test data. Laboratory data gathered from many experiments using materials transported in 50 to 100 mm diameter dense phase conveying test rigs is available (44). The test methodology, and the techniques for scale-up of pressure transporter test rig data to industrial sized systems, should be of interest. Theory and applications of pneumatic conveying can be found in Reference 42 and information on conveying equipment and applications in References (44–48).

3. Economic Aspects

The bulk solids conveying industry is interwoven with all aspects of the chemical industry, from mining of raw materials to in-process handling and to final product delivery. The 1987 value of U.S. product shipments of bulk conveyors and parts was $2.11 billion according to CEMA. Lists of conveyor manufacturers in the United States (49–51), and worldwide (52) are available.

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