

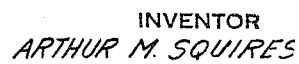
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APPARATUS AND METHOD FOR CONVEYING DRY PULVERULENT
SOLID IN LIQUID-LIKE STATE

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2 Sheets-Sheet 1



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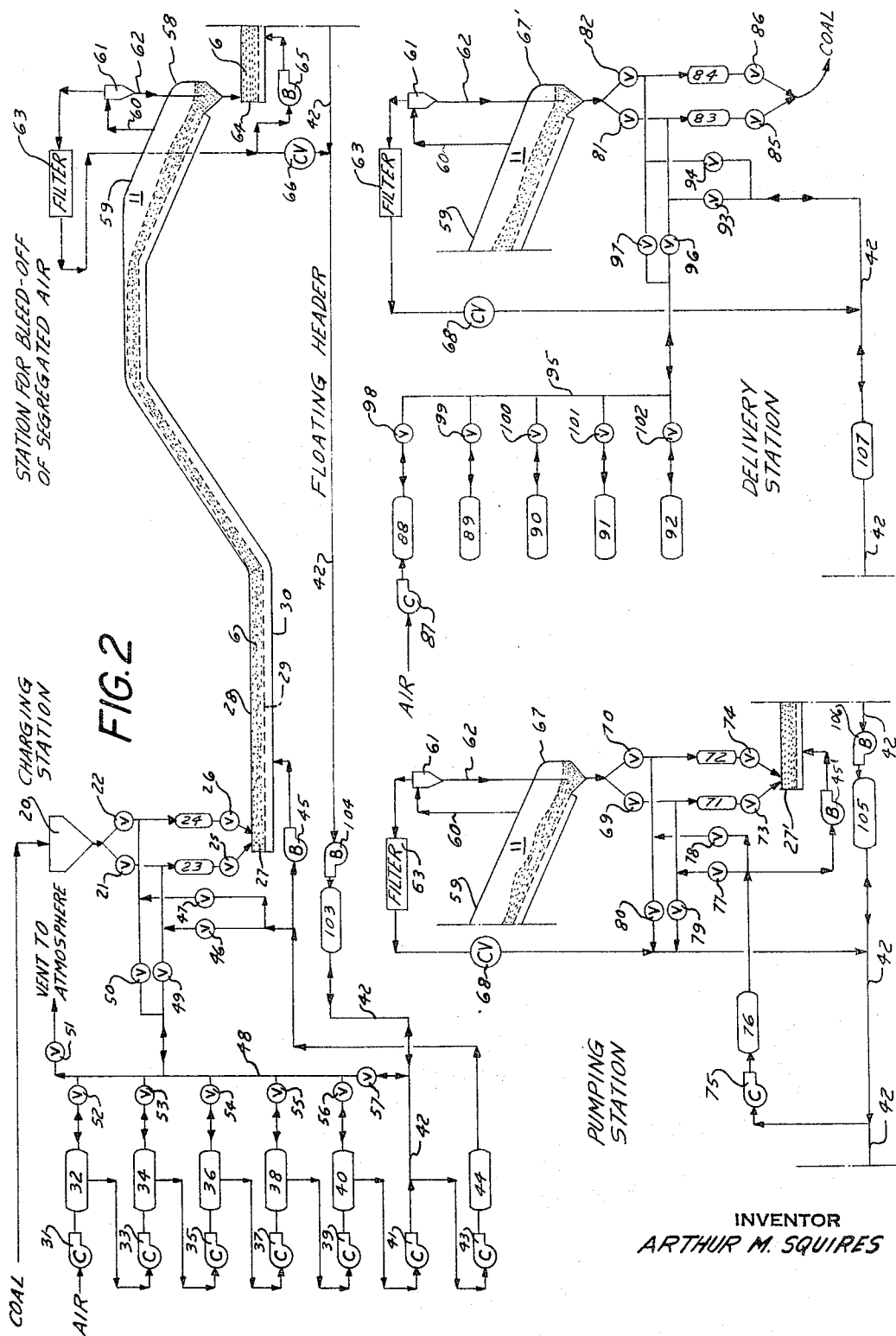
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**APPARATUS AND METHOD FOR CONVEYING
DRY PULVERULENT SOLID IN LIQUID-
LIKE STATE**

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This invention pertains to the conveying of a pulverulent solid in a generally horizontal direction, for long distances, through the action of a gaseous conveying medium.

An object of the invention is to provide an improved means of conveying a pulverulent solid, such as finely divided coal, cement, iron ore, or the like, across country for distances of many miles.

Vast quantities of coal are shipped long distances for use in steampower electricity-generating plants. Charges for shipping coal to such plants often represent a significant portion of final electricity costs. With the object of reducing these shipping charges, much consideration has been given to coal pipelines employing water as the conveying medium. A large pilot line has been built and operated for several years, and projects have been proposed which would deliver as much as 10,000,000 tons per year of coal through a single line hundreds of miles long.

Hydraulic conveying of coal has the serious disadvantage that coal is delivered to the power station wet. Drying of the coal prior to its firing in a boiler is costly, and the firing of a slurry of coal and water—means for doing so have been worked out for one type of modern power-station boiler—inevitably results in waste of the heat needed to vaporize water in the slurry.

Proposals have been made for the pneumatic conveying of coal across long distances. This would have the advantage of delivering coal dry, but power requirements for pneumatic conveying of coal by known means are considerably greater than power needed to pump a slurry of coal and water.

An object of the present invention is to permit the delivery of coal in a dry state across long distances at an expenditure of power comparable to needs for hydraulic conveying.

I have found that a pulverulent solid may be caused to flow through a closed conduit in a liquid-like state through agency of a pressure drop in a minimal quantity of gas. The solid flows at a density substantially comparable to its settled density in a bin, and I provide arrangements whereby the solid occupies a substantial portion of the cross-section of the conduit throughout its length, no matter how great. Since the solid flows in a dense state, the solid-conveying capacity of a conduit of given cross-section is large. Since a minimal quantity of gas is used to sustain the solid flow, the horsepower expended for gas compression is outstandingly small. Pressure gradients along the conduit are small, and pumping stations can be far apart.

Fine powders have the property of forming liquid-like emulsions with air or other gas. These emulsions are relatively "stable" in a sense to be discussed hereinafter.

If a gas is introduced into a bed of fine powder from beneath—by means of an aeration pad, for example—the gas exerts a lifting action on the powder. With gradual increase of gas rate, a value is reached at which the powder is rendered effectively weightless. This gas rate is identified with the "minimum buoyancy velocity," a velocity customarily expressed on a "superficial" basis; that is to say, the velocity of gas flowing upward through the bed of powder is calculated as if the powder were not present. As this gas rate is exceeded, the mass of

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powder generally swells in volume, and swelling continues until the gas rate reaches a value identified with the "minimum bubbling velocity," also customarily expressed on a superficial basis. At still higher gas rates, gas bubbles appear in the bed. The swollen gas-powder system which exists between the minimum buoyancy and minimum bubbling velocity forms an "emulsion" having many liquid-like properties. The powder has "imbibed" a quantity of gas. This imbibed gas forms tiny upward-flowing gas currents, generally obeying a pressure-flow relationship of the Poiseuille form. These gas currents separate the particles, which effectively rest upon "films" of gas rather than upon each other.

Gas-powder emulsions exhibit a degree of stability against loss of flow of aeration gas. If aeration gas (i.e., "emulsifying" gas) is cut off, the action of gravity "pumps" the imbibed gas films from the emulsion, and the mass of powder settles back to something like its original volume. For powders such as pulverized coal of the fineness generally employed in firing most modern steam-power boilers, a bed as shallow as eight inches retains some liquid-like character for six seconds or longer after flow of aeration gas stops. Cement behaves in a similar fashion, while powdered iron ore loses its liquid-like character somewhat faster on account of its higher intrinsic density.

I have found that liquid-like flow of a gas-powder emulsion can be maintained throughout the length of a generally horizontal conduit by supplying sufficient emulsifying gas through the underside of the conduit. The conduit is provided with a porous pad which occupies a sufficient portion of the bottom, and through which gas flows at a sufficient rate, to maintain the liquid-like character of the gas-powder emulsion. It is not generally required that the emulsifying-gas pad occupy the entire bottom of the conduit, either in the lateral or longitudinal direction of the conduit. This is because the gas-powder emulsion is relatively stable against loss of liquid-like character, in the sense just described. The emulsion can safely exist and flow for short intervals of time in absence of a renewal of emulsifying gas. I prefer to operate the conduit at solids rates which lead to existence of liquid-like turbulence in the liquid-like mass of solid, since such turbulence cooperates with the emulsifying gas to maintain the solid in a liquid-like state. Existence of turbulence makes possible a use of less emulsifying gas than would otherwise be needed.

I have found that the pressure gradient necessary to cause flow of the liquid-like gas-powder emulsion can be estimated using known correlations for flow of two-phase gas-liquid mixtures. I will explain hereinafter the exact manner in which I use these correlations, but I remark here that the applicability of these correlations provides a most useful criterion and method for determining the extent to which the emulsifying-gas pad must cover the bottom of the conduit, as well as the amount of emulsifying gas which must be supplied. If the extent of pad or amount of gas is insufficient, there is a dramatic increase in pressure gradient beyond that which can be calculated from the correlations for flow of two-phase gas-liquid mixtures. Accordingly, an adjustment must be made in one or both of the foregoing variables governing the admission of emulsifying gas. One wishes to use as little emulsifying gas as possible, for supply of this gas requires an expenditure of power. I have not found a general method whereby the minimum quantity of emulsifying gas may be determined for a particular situation. I believe that the minimum quantity is affected primarily by the variable: solid particle size and density, gas density and viscosity, and effective Reynolds Number for flow of the gas-solid emulsion (in a sense to be defined

hereinafter). Be that as it may, the dramatic and drastic increase in pressure gradient, when supply of emulsifying gas is insufficient, considered alongside a calculation procedure for estimating the proper pressure gradient for best working of my invention, provides a ready approach for quickly working out the best arrangement for supply of emulsifying gas in a given situation.

Means are already known for causing solid to move through a substantially horizontal pipe or conduit in a substantially settled or dense state.

One such means is to feed solid into a pipe from a pressurized hopper or from a screw pump. Sometimes aeration gas is added to the solid at or near the point of entry of solid into the pipe. However, any liquid-like character thereby imparted to the solid is quickly lost as the solid moves along the pipe. The average pressure gradient along the entire pipe, if any appreciable distance is traversed, is much greater than the average gradient attainable by my new method. Dense solid is forced through the pipe, generally in the form of "slugs" of high density separated by pockets of gas which are relatively free of solid. The superficial velocity of gas through the pipe—i.e., the gas velocity calculated in the direction of the axis of the pipe as if no solid were present—is generally far greater than that required by my new method. Power needs are greater, both on account of greater pressure drop and greater flow of gas.

Another known means of causing solid to move in a generally horizontal direction is to provide an aeration pad across the entire bottom of a conduit, supplying aeration gas in an amount sufficient to place the solid in the fluidized state, and to allow the solid to flow under the action of gravity. The body of flowing solid is shallow, occupying only a minor portion of the conduit. Sometimes the conduit is open at the top, allowing free escape of aeration gas along the conduit's entire length. Sometimes the conduit is closed, but in this case the flow of gas in the space above the moving solid is incidental to the disposal of the gas via dust-removal equipment. This flow of gas does not contribute substantially to aiding flow of solid. The pressure gradient along a conduit of this type is generally negligibly small. This method of solid transport is limited to a transfer of a solid from a higher to a lower elevation. Because of the method's low pressure gradient, because of its ability to operate at substantially atmospheric pressure, and because of small gas-compression power needed, it is a preferred method for down-hill transfer of a finely divided solid.

My invention and its advantages will be more fully understood by reference to the accompanying drawings and the following description thereof:

FIG. 1 provides six typical cross-sectional views of a form of conveying duct suitable for operation of my invention. Three views, designated FIGS. 1a, 1b, and 1c, are cross-sections perpendicular to the direction of solid flow, shown at representative positions along the conveying duct. Three views, designated FIGS. 1d, 1e, and 1f, are vertical cross-sections along the axis of the duct, at the same respective representative positions.

FIG. 2 provides a general diagram of an installation of my invention suitable for conveying finely pulverized coal for long distances.

FIGS. 1a and 1d illustrate the situation near a point at which solid is fed to the conveying duct. FIG. 1a is a cross-section of the duct perpendicular to direction of solid flow, and FIG. 1d is a vertical cross-section along the axis of the duct. Round pipe 1 is fabricated of metal of sufficient thickness to maintain a substantially super-atmospheric pressure in the space within. A solid-conveying space is enclosed by thin metal wall 2a and emulsifying-gas pad 3, which is fabricated of a porous medium, such as porous sintered metal or ceramic or synthetic plastic material, porous fabric, or the like. A liquid-like mass of solid, designated by 6, occupies substantially the entire region enclosed by wall 2a and pad 3. Metal wall

2a is continuous with metal wall 2b, and space 4 is formed between metal walls 2a and 2b and the outer pipe 1. Metal wall 2b together with pad 3 enclose space 5. Space 4 communicates with space 5 through nozzles 7. Situated above each nozzle 7 is a horizontal plate 8, which may be circular, rectangular, or of other suitable shape. FIG. 1d shows vertical baffles 9 which substantially divide space 5 into longitudinal compartments, although it is not necessary that baffles 9 seal tightly against pad 3. The assembly enclosed by walls 2a and 2b may be suitably supported within pipe 1, as for instance by brackets 12 resting on the bottom of pipe 1 and engaging walls 2b.

Space 4 is maintained at a pressure a few pounds per square inch (p.s.i.) above liquid-like solid mass 6. The size of nozzles 7 and the porosity of pad 3 are chosen so that emulsifying gas flows from space 4 via nozzles 7 and pad 3 into solid 6 at a superficial velocity higher than the minimum buoyancy velocity of the solid. Plate 8 serves to dissipate the high-velocity jet emerging from a nozzle 7, so that the pressure on the underneath side of pad 3 is reasonably uniform within a given compartment formed by baffles 9.

By withdrawing solid at a downstream end of the conveying duct, and by feeding an equivalent amount of solid at an inlet end, a flow of solid is maintained at a rate such that the Reynolds Number (in a sense to be defined hereinafter) is well above 2,000, so that flow is in the turbulent regime.

At an inlet end of the conveying duct, substantially the only gas flowing along with solid is interstitial gas, and liquid-like mass 6 substantially fills the cross-section of the conveying duct. Interstitial gas moves at substantially the same velocity as the solid, and the superficial gas velocity along the duct is simply solids velocity times the fraction of space which is occupied by interstitial gas.

As solid moves along the duct, emulsifying gas is introduced in an amount sufficient to maintain the solid in the liquid-like state. Accordingly, the superficial gas velocity through the duct increases, and I have found that gas tends to segregate from solid to form a low-solid-density zone in the upper part of the conduit. This situation is illustrated by FIGS. 1b and 1e, wherein common numerals designate elements which are common to FIGS. 1a and 1d. FIGS. 1b and 1e are identical to FIGS. 1a and 1d respectively, save for presence of low-solid-density zone 10 above dense liquid-like mass 6 of solid. The gas velocity through zone 10 is appreciably greater than the solid velocity in mass 6.

I have found empirically that the pressure gradient through a horizontal duct of the type exemplified by FIGS. 1a and 1d, or by FIGS. 1b and 1e, can be estimated with an accuracy sufficient for engineering purposes from the following formula:

$$\frac{\Delta P}{L} = \frac{2f(W/A)^2}{32.2D\rho_s S^{0.87}} \times \frac{5280}{144}$$

where

$\Delta P/L$ = pressure gradient expressed in p.s.i. per mile;

W = combined mass flow of solid and gas through the duct in pounds per second;

A = cross-sectional area of duct defined by wall 2a and pad 3 in square feet;

D = "equivalent" diameter of aforesaid duct in feet = $4 \times A$ divided by perimeter in feet;

ρ_s = loosest settled density of solid in pounds per cubic foot, i.e., the density determined by first shaking a weighed sample of solid vigorously up and down in a graduate cylinder and then noting the volume to which the sample settles without undue vibration or tapping;

S = a calculated volume fraction of the solid "phase" flowing in the "two-phase" solid-gas mixture, the solid being assigned its loosest settled density, thus:

$$S = \frac{W_s/\rho_s}{(W_s/\rho_s) + W_g(1-\epsilon)/\rho_g}$$

where W_s and W_g are the weight rates of flow of solid and gas respectively in pounds per second, ρ_g is the density of gas in pounds per cubic foot, and dimensionless ϵ is the volume fraction of solid occupied by interstitial gas when solid is at its loosest settled density ρ_s ;
 f =dimensionless friction factor determined from published correlation of friction factor versus dimensionless Reynolds Number Re for homogeneous (i.e., single-phase) fluid flow through a smooth-walled pipe of diameter D ; and
 $Re=DW/0.000672 A$.

The foregoing formula is an adaptation of a known correlation for two-phase gas-liquid flow. The adaption credits the liquid-like solid state with a density equal to the loosest settled density and with a viscosity of 1 centipoise, substantially the viscosity of liquid water at normal temperatures. The adaption places all gas into the segregated, low-solid-density zone 10, other than interstitial gas in solid at its loosest settled density. The formula should not be used if S is smaller than about one-tenth, but there is little practical interest in S -values smaller than about one-tenth. Should such smaller S -values be encountered, published correlations for two-phase gas-liquid flow, I have found, still give reasonably accurate estimates of pressure gradient for the gas-solid case, in a duct exemplified by FIGS. 1b and 1e, if the correlations are used in the spirit set forth above.

The empirical crediting of the liquid-like solid "phase" with a viscosity of 1 centipoise is in accord with my experience, but those skilled in the art will recognize that flow experiments conducted in the turbulent regime do not provide a precise judgment with respect to viscosity. Those skilled in the art will recognize that using a viscosity differing from 1 centipoise by an order of magnitude in either direction would have little effect, from a practical engineering standpoint, upon the pressure gradients calculated from the foregoing formula, provided Re is appreciably greater than 2,000.

I should note, as a precaution, that two different conventions exist in the engineering literature with regard to the definition of friction factor f . To those skilled in the art, it will be clear from the foregoing formula that I have used the convention by which f -values are one-quarter the values which they take on according to an alternate convention which is sometimes used. Before employing a given published form of the correlation of f versus Re in a calculation, one should ascertain (by comparing the form of the correlation with my formula above) which convention has been used, lest answers be calculated which are incorrect by a factor of 4.

Notice should be taken that the fraction S is calculated from the FLOWING quantities of solid and gas. The fraction S is NOT related to the relative cross-sectional areas of space 10 and solid mass 6 (as depicted in FIGS. 1b and 1e), since gas flows along space 10 at a far higher velocity than the velocity of solid mass 6. Knowledge of the relative areas of space 10 and solid mass 6 is therefore not required to use the foregoing empirical formula.

Nevertheless, it should be understood that the motion of gas at high velocity along space 10 is a powerful factor in aiding the forward movement of solid mass 6. This is in contradistinction to the aforementioned down-hill system of conveying, where gas motion in the space above the fluidized mass of solid contributes little if any aid to solid motion.

The foregoing formula fully takes into account the help toward motion is solid mass 6 contributed by gas flow along space 10.

As noted earlier, the foregoing formula is a guide to determining the best arrangement for supply of emulsifying gas for a particular application of my invention. If emulsifying gas is inadequate, the pressure gradient for a given solids throughput is drastically higher than that calculated from the foregoing formula.

It is worth noting that the pressure gradient pertaining

to my new technique of solid conveying is always as great or greater than the gradient which would be observed were one to pass a liquid through a similar conduit at the same mass rate, the liquid having a viscosity of the order of 1 centipoise and a density equal to the loosest settled density of the solid. This fact is seen by substituting $W=W_s$ and by setting $S=1$ in the foregoing formula. Much smaller pressure gradients are characteristic of the aforementioned down-hill system of conveying, and such gradients are merely incidental to the disposal of fluidizing gas.

FIGS. 1d and 1e show the duct as if it were perfectly horizontal. In fact, I have found that a duct of this type can carry solids up-hill at steep angles. The pressure gradient in such case is simply estimated by adding the energy loss required to lift the solids, according to the Bernoulli principle, to the pressure gradient estimated from the foregoing formula.

An alternate form of duct, sometimes preferred for down-hill sections of duct, is displayed in FIGS. 1c and 1f, which show respectively a cross-section perpendicular to the direction of flow and a vertical cross-section along the axis of the duct. Round pipe 1 serves the same function as in FIGS. 1a and 1d, already described, and a solid-conveying conduit is enclosed by metal wall 2a' and emulsifying-gas 3', which substantially covers the bottom of the conduit defined by wall 2a' and pad 3'. Metal wall 2a' is continuous with metal wall 2b', and space 4' is formed between metal walls 2a' and 2b' and outer pipe 1. Metal wall 2b' together with pad 3' enclose space 5'. Space 4' communicates with space 5' through nozzles 7'. Situated above each nozzle 7' is a horizontal plate 8', which may be circular, rectangular, or of other suitable shape. Space 4' is at a higher pressure than the space enclosed by wall 2a' and pad 3'. Nozzles 7' and pad 3' cooperate to maintain a flow of emulsifying gas across pad 3' at a rate higher than the minimum buoyancy velocity of the solid. Liquid-like mass 6 is supported by pad 3', and flow of solid 6 is maintained by the action of gravity. In general, solid mass 6 is shallow, and low-solid-density zone 11 is large by comparison with low-solid-density zone 10 in FIGS. 1b and 1e. Gas velocity in low-solid-density zone 11 is relatively low. Pressure gradient in a down-hill section of duct built according to FIGS. 1c and 1f is small. In order further to reduce gas velocity in zone 11, pipe 1 may be made larger in down-hill sections of duct built according to FIGS. 1c and 1f. This is advantageous at certain locations in a cross-country line, for a reason to be set forth hereinafter.

In an example, I visualized a need to convey powdered coal cross-country at a rate of 640 pounds per second (i.e., approximately 10,000,000 tons per year). The coal had the fineness customarily used in the firing of most modern steam-power boilers, viz., substantially all of the coal passed through a 170-mesh screen. The coal had a loosest settled density of 37.9 pounds per cubic foot in atmospheric air. I used a duct having a cross-sectional area $A=3.687$ square feet (equivalent to a 26-inch pipe), and I operated the duct with air as the conveying medium and at pressures between 1000 pounds per square inch absolute (p.s.i.a.) and 700 p.s.i.a. I believe the minimum buoyancy velocity of this coal in air at these pressures to be less than 0.03 ft./sec. Using the above formula, I estimated a pressure gradient of about 3.5 p.s.i. per mile at a point at which coal was fed to the duct, viz., at a point at which the duct ran substantially full of coal, as in FIGS. 1a and 1d. I allowed the introduction of emulsifying air via pad 3, at a rate of 79.2 cubic feet per second per mile, to maintain a liquid-like state throughout the duct. I used an emulsifying-gas pad 3 six inches wide, so that emulsifying gas entered the conduit at a velocity in the vertical direction of 0.03 ft./sec. Using the above formula, I judged the pressure gradient to increase from 3.5 p.s.i. per mile at a point of coal feed to 6.6 p.s.i. per mile

at a point one-eighth of a mile away. At the latter point, the fraction S was about 0.63, and the flow of segregated air was roughly comparable to the flow of interstitial air. The integrated pressure drop across the afore-described one-eighth mile of conveying duct was about 0.625 p.s.i. At the end of a one-eighth-mile section of conveying duct, I elected to bleed off a quantity of air comparable to the quantity of emulsifying air introduced into the duct throughout the one-eighth-mile section. To facilitate this bleed-off of air, I introduced a short down-hill stretch of duct built according to FIGS. 1c and 1f, and I withdrew air via a connection to the top of space 11 passing through the wall of pipe 1. The mode of withdrawing air will be understood more clearly from the discussion of FIG. 2 below.

FIG. 2 depicts schematically a complete system for conveying powdered coal across a distance of hundreds of miles. I will describe the operation of FIG. 2 in connection with the foregoing example, in which 640 pounds per second of coal was conveyed by air at duct pressures ranging from 1000 p.s.i.a. to 700 p.s.i.a.

For simplicity's sake, the cross-country coal-conveying duct is indicated in FIG. 2 in a highly schematic fashion, viz., an upper solid line 28, a lower solid line 30, and a dashed line 29 intermediate to lines 28 and 30. The space between lines 28 and 29 represents the actual coal-conveying conduit, enclosed by wall 2a or 2a' and pad 3 or 3' in FIG. 1. Liquid-like coal mass 6 is shown between lines 28 and 29 in FIG. 2. The space between lines 29 and 30 in FIG. 2 represents space 4 or 4' in FIG. 1. Dashed line 29 of FIG. 2 represents the combination of nozzles 7 or 7', plates 8 or 8', space 5 or 5', and pad 3 or 3' in FIG. 1—viz., the elements which regulate the flow of emulsifying air into coal mass 6.

A coal-charging station is provided at feed end 27 of the coal-conveying duct, which is maintained at 1000 p.s.i.a. A primary object of the coal-charging station is to raise the pressure of coal to 1000 p.s.i.a.—more accurately put, to raise the pressure of interstitial air accompanying coal to 1000 p.s.i.a.—so that coal may be introduced into feed end 27. FIG. 2 illustrates apparatus for accomplishing this object with expenditure of outstandingly small horsepower for compression of air. The quantity of air which must be compressed from the atmosphere is only a tiny fraction of the quantity of interstitial air which accompanies coal into feed end 27.

Coal is fed from the atmosphere to atmospheric-pressure bin 20, from which coal flows intermittently via either valve 21 or valve 22 into respective lock-hopper 23 or 24. The lock-hopper receiving coal at a given moment is at atmospheric pressure. The lock-hopper not receiving coal is pressured with air to 1000 p.s.i.a., and feeds coal at this pressure via either valve 25 or 26 into feed end 27.

Air for pressuring coal to 1000 p.s.i.a. is supplied by compressors 31, 33, 35, 37, 39, 41, and 43, each operating continuously. Compressor 31 draws a relatively small quantity of air from the atmosphere and discharges into surge-chamber 32. Compressor 33 draws a significantly larger quantity of air from surge-chamber 32 and discharges into surge-chamber 34. Compressors 35, 37, 39, and 41 draw air from surge-chambers 34, 36, 38, and 40 respectively. Compressors 35, 37, and 39 discharge air into surge-chambers 36, 38, and 40 respectively. Compressor 41 discharges air into cross-country line 42, a pipe paralleling the coal-conveying duct. Line 42 serves as a "floating header" through which air flows from the delivery end of the coal-conveying duct toward the coal-charging station, this air supplying a portion of air needed to pressure coal to 1000 p.s.i.a. Compressor 43 draws air from floating header 42 and discharges into a surge-chamber 44. The quantity of air handled by each of compressors 33, 35, 37, 39, 41, and 43 is substantially greater than the quan-

tity of air handled by the preceding compressor in the numerical sequence. Each of surge-chambers 32, 34, 36, 38, 40, and 44 is large in comparison with a lock-hopper 23 or 24. The surge-chambers operate at pressures which fluctuate through small intervals about mean values of approximately 40, 100, 200, 350, 500, and 1000 p.s.i.a. respectively. Deep-cavern space excavated in solid rock may advantageously be used to serve as one of these surge-chambers. Floating header 42 operates at a pressure which fluctuates through a small interval about a mean value of approximately 700 p.s.i.a.

Air for pressuring coal to 1000 p.s.i.a. is drawn from surge-chamber 44. Also, emulsifying air from the first approximately one-eighth-mile section of the coal-conveying duct is supplied from surge-chamber 44 via blower 45, which raises the pressure of this emulsifying air to approximately 2 p.s.i. above the pressure of coal mass 6 at feed end 27 of the duct.

Lock-hoppers 23 and 24 may be placed in communication with surge-chamber 44 via valves 46 and 47 respectively. Lock-hoppers 23 and 24 may be placed into communication with a line 48 via valves 49 and 50 respectively. Line 48 may be placed in communication with the atmosphere, surge-chambers 32, 34, 36, 38, and 40, and floating header 42 via valves 51, 52, 53, 54, 55, 56, and 57 respectively.

The charging-station valving cycle will be described for lock-hopper 23 starting from the situation where lock-hopper 23 stands empty of coal and is pressured with air at 1000 p.s.i.a. Valve 21 and valves 49 through 57 are closed. During the cycle to be described, lock-hopper 24 is feeding coal at 1000 p.s.i.a. via valve 26 into feed end 27. Valve 22 is closed. Valve 47 is open, so that air at 1000 p.s.i.a. may flow continuously from surge-chamber 44 into lock-hopper 24. As lock-hopper 24 is discharged, an amount of air flows into lock-hopper 24 corresponding to the volume previously occupied by coal.

The valving cycle for lock-hopper 23 is as follows:

(1) Close valves 25 and 46, isolating lock-hopper 23 from conveying-duct feed end 27 and surge-chamber 44 respectively.

(2) Open valve 49, placing lock-hopper 23 in communication with line 48.

(3) Open valve 57, depressuring lock-hopper 23 from 1000 p.s.i.a. to about 700 p.s.i.a. by allowing air to flow into floating header 42, whose volume should be so great by comparison with the volume of lock-hopper 23 that there is only a small increase in pressure in header 42 caused by this flow of air.

(4) Close valve 57 and open valve 56, depressuring lock-hopper 23 from 700 p.s.i.a. to about 500 p.s.i.a. by flow of air into surge-chamber 40. There is only a small increase in pressure in surge-chamber 40.

(5) Close valve 56 and open valve 55, depressuring lock-hopper 23 from 500 p.s.i.a. to about 350 p.s.i.a. by allowing air to flow into surge-chamber 38.

(6) Close valve 55 and open valve 54, depressuring lock-hopper 23 from 350 p.s.i.a. to about 200 p.s.i.a. by allowing air to flow into surge-chamber 36.

(7) Close valve 54 and open valve 53, depressuring lock-hopper 23 from 200 p.s.i.a. to about 100 p.s.i.a. by allowing air to flow into surge-chamber 34.

(8) Close valve 53 and open valve 52, depressuring lock-hopper 23 from 100 p.s.i.a. to about 40 p.s.i.a. by allowing air to flow into surge-chamber 32.

(9) Close valve 52 and open valve 51, venting air from lock-hopper 23 to the atmosphere.

(10) Leaving valve 51 open, open valve 21 allowing coal to fill lock-hopper 23 from bin 20.

(11) Close valves 21 and 51.

(12) Open valve 52, pressuring lock-hopper 23 to about 40 p.s.i.a. from surge-chamber 32.

(13) Close valve 52 and open valve 53, pressuring lock-hopper 23 to about 100 p.s.i.a. from surge-chamber 34.

(14) Close valve 53 and open valve 54, pressuring lock-hopper 23 to about 200 p.s.i.a. from surge-chamber 36.

(15) Close valve 54 and open valve 55, pressuring lock-hopper 23 to about 350 p.s.i.a. from surge-chamber 38.

(16) Close valve 55 and open valve 56, pressuring lock-hopper 23 to about 500 p.s.i.a. from surge-chamber 40.

(17) Close valve 56 and open valve 57, pressuring lock-hopper 23 to about 700 p.s.i.a. from floating header 42.

(18) Close valves 57 and 49, and open valve 46, pressuring lock-hopper 23 to 1000 p.s.i.a. from surge-chamber 44. Lock-hopper 23 now stands ready to deliver coal at 1000 p.s.i.a. to feed end 27, by opening valve 25, as soon as lock-hopper 24 is emptied of coal.

The valving cycle for lock-hopper 24 will be clear from the foregoing description of the cycle for lock-hopper 23.

The purpose of providing the series of surge-chambers and the sequential step-wise depressuring of a lock-hopper is to conserve pressure in air. Horsepower requirements to supply 1000 p.s.i.a. air for pressuring coal would be much greater if a lock-hopper were vented from 1000 p.s.i.a. to the atmosphere in one step; or, as is sometimes practiced, if the pressure of two lock-hoppers, one at high pressure and empty of coal and the other at atmospheric pressure and full of coal, is equalized by placing the lock-hoppers in communication before venting the first and pressuring the second to full duct pressure.

The quantity of air drawn from the atmosphere by compressor 31 amounts only to the quantity of air vented from lock-hopper 23 at step 9 above, less the quantity of atmospheric-pressure interstitial air entering lock-hopper 23 along with coal arriving from bin 20.

In FIG. 2, the section of conveying duct between 27 and 58 is a highly schematic representation of the first approximately one-eighth mile of duct. This terminates with an arrangement for bleed-off of segregated gas, which substantially represents the influx of emulsifying gas across 29 through the first one-eighth mile of duct. A down-hill stretch is provided, as indicated at 59, constructed as represented in FIGS. 1c and 1f and preferably having an outer pipe 1 somewhat larger than other portions of the duct. Gas is withdrawn from the upper, low-solid-density zone 11 of the conduit, via line 60. Dust is largely removed from this gas by means of cyclone 61, and dust is returned to the conveying duct via cyclone-dip-leg 62. Dust is finally removed from the gas by filter 63. Solid flows by gravity at substantially its loosest settled density, without significant loss of pressure, from the terminus 58 of the first one-eighth-mile of duct into the feed end 64 of the second one-eighth-mile of duct. Most of the air removed from the duct via line 60 is boosted in pressure by means of blower 65 to a level approximately 2 p.s.i. above the pressure of coal mass 6 at feed end 64. Air from blower 65 serves as emulsifying gas for the second one-eighth-mile of duct. A small quantity of air from filter 63 is removed across control valve 66 into floating header 42. This small quantity is regulated so that the volumetric flow through blower 65 is substantially the same as that through blower 45. This small quantity of air represents the increase in volume brought about by expansion of both interstitial gas and emulsifying gas introduced into the first one-eighth-mile of duct, the expansion being a consequence of the decline in pressure of about 0.625 p.s.i. in this section of duct.

Equipment similar to items 59 through 66 is installed at intervals of approximately one-eighth mile throughout the entire length of the coal-conveying duct.

When a point 67 is reached at which the pressure in the coal-conveying duct has fallen to about 700 p.s.i.a. (but not below the pressure in floating header 42), a "pumping station" is provided. This point is expected to be about 60 miles from the start of the duct. The object of the

pumping station is to raise the pressure of the coal from 700 to 1000 p.s.i.a., so that it may be fed to inlet end 27' of a second 60-mile segment of duct. At the pumping station, equipment items 59 through 63 function substantially in the manner just described for equivalent items at a station for bleed-off of segregated gas. Control valve 68 passes all gas bled from the conveying duct via line 60 into floating header 42. Coal from point 67 is discharged, substantially at its loosest settled density, via either valve 69 or valve 70, into respective lock-hopper 71 or 72. The lock-hopper receiving coal at a given moment is at 700 p.s.i.a. and is in communication with floating header 42 via either valve 79 or 80. As a lock-hopper receives coal at 700 p.s.i.a., air is forced from the lock-hopper into floating header 42.

Air for re-pressuring coal from 700 p.s.i.a. to 1000 p.s.i.a. is supplied from surge-chamber 76 at 1000 p.s.i.a., which is large by comparison with lock-hoppers 71 and 72. Air to surge-chamber 76 is supplied from floating header 42 by means of compressor 75. Lock-hoppers 71 and 72 may be placed in communication with surge-chamber 76 via valves 77 and 78 respectively.

The pumping-station valving cycle will be described for lock-hopper 71 starting from the situation where lock-hopper 71 stands empty of coal and is pressured with air at 1000 p.s.i.a. Valves 69, 79, and 80 are closed. During the cycle to be described, lock-hopper 72 is feeding coal at 1000 p.s.i.a. via valve 74 into inlet end 27'. Valve 70 is closed. Valve 78 is open, so that air at 1000 p.s.i.a. may flow continuously from surge-chamber 76 into lock-hopper 72, to occupy volume made empty by the discharge of coal.

The valving cycle for lock-hopper 71 is as follows:

(1) Close valves 73 and 77, isolating lock-hopper 71 from feed end 27' and surge-chamber 76 respectively.

(2) Open valve 79, depressuring lock-hopper 71 from 1000 p.s.i.a. to about 700 p.s.i.a. by allowing air to flow into floating header 42.

(3) Open valve 69, allowing coal to flow into lock-hopper 71 at 700 p.s.i.a. from terminus 67 of the first 60 miles of coal-conveying duct. As coal enters lock-hopper 71, air is displaced into floating header 42.

(4) When lock-hopper 71 is full of coal, close valves 69 and 79, and open valve 77, pressuring lock-hopper 71 to 1000 p.s.i.a. by flow of air from surge-chamber 76. Lock-hopper 71 is now ready to deliver coal to feed end 27'.

Terminus 67 of the first 60 miles of coal-conveying duct must provide sufficient volume to hold coal which accumulates during the short time interval during which neither lock-hopper is prepared to receive coal. Alternatively, three lock-hoppers like 71 and 72 could advantageously be provided to assure continuity both of receiving coal from terminus 67 and also of delivering coal to feed end 27'.

Emulsifying air to the first one-eighth-mile section of the second 60-mile segment of duct is supplied by blower 45' drawing air from surge-chamber 76.

At the terminus of the cross-country coal-conveying duct, a "delivery station" is provided. Advantageously, the delivery station is situated at a point 67', at which the pressure in the coal-conveying duct has fallen to about 700 p.s.i.a. If the distance traversed by the entire system is approximately an integer times 60 miles, no modification of the foregoing description of the pumping station is needed. If the final segment of duct is shorter than 60 miles, the pressure level in surge-chamber 76 of the final pumping station and at feed end 27' of the final segment of duct can be correspondingly lower than 1000 p.s.i.a.

At the delivery station, equipment items 59 through 63 function substantially in the manner as equivalent items at a station for bleed-off of segregated gas, already described. Control valve 68 passes all gas bled via line 60 into floating header 42. Coal from terminus 67' is discharged, substantially at its loosest settled density, via

either valve 81 or valve 82 into respective lock-hopper 83 or 84. The lock-hopper receiving coal at a given moment is at 700 p.s.i.a. and is in communication with floating header 42 via either valve 93 or 94. The lock-hopper not receiving coal from the coal-conveying duct at a given moment is pressured to about 35 p.s.i.a. (in a manner to be described hereinafter) and is delivering coal at this pressure via either valve 85 or 86 to means for using or storing the coal (not shown in FIG. 2).

The primary object of the delivery station is to deliver coal at the relatively low pressure of about 35 p.s.i.a.—which is ample to convey the coal a short distance, of the order of a few hundred feet, to means for using or storing the coal—while recovering substantially ALL of the air arriving along with the coal at point 67' at the full duct pressure of 700 p.s.i.a. which prevails at point 67'. This air is returned via floating header 42 toward the feed end of the duct. I have discovered that this object can be accomplished most conveniently if air is supplied from the atmosphere to accompany the delivered coal. It was a surprise to me that supply of air from the atmosphere is preferable to using a portion of air arriving at point 67' along with coal as the transport medium to deliver coal at a relatively low pressure.

Air for delivery of coal at about 35 p.s.i.a. is supplied continuously from the atmosphere via compressor 87, which discharges air into surge-chamber 88, which operates at about 35 p.s.i.a. Surge-chambers 89, 90, 91, and 92 are also provided, operating respectively at about 64 p.s.i.a., about 116 p.s.i.a., about 212 p.s.i.a., and about 385 p.s.i.a. Each of surge-chambers 88, 89, 90, 91, and 92 is large in comparison with a lock-hopper 83 or 84.

Lock-hoppers 83 and 84 may be placed into communication with a line 95 via valves 96 and 97 respectively. Line 95 may be placed in communication with surge-chambers 88, 89, 90, 91, and 92 via valves 98, 99, 100, 101, and 102 respectively.

The delivery-station valving cycle will be described for lock-hopper 83 starting from the situation where lock-hopper 83 stands full of coal and is pressured with air at 700 p.s.i.a. Valve 85 and valves 96–102 are closed. During the cycle to be described, lock-hopper 84 is receiving coal at 700 p.s.i.a. via valve 82 from terminal end 67' of the duct. Valve 86 is closed. Valve 94 is open, so that air displaced by coal entering lock-hopper 84 flows into floating header 42.

The valving cycle for lock-hopper 83 is as follows:

(1) Close valves 81 and 93, isolating lock-hopper 83 from terminal end 67' and floating header 42 respectively.

(2) Open valve 96, placing lock-hopper 83 in communication with line 95.

(3) Open valve 102, depressuring lock-hopper 83 from 700 p.s.i.a. to about 385 p.s.i.a.

(4) Close valve 102 and open valve 101, depressuring lock-hopper 83 to about 212 p.s.i.a.

(5) Close valve 101 and open valve 100, depressuring lock-hopper 83 to about 116 p.s.i.a.

(6) Close valve 100 and open valve 99, depressuring lock-hopper 83 to about 64 p.s.i.a.

(7) Close valve 99 and open valve 98, depressuring lock-hopper 83 to about 35 p.s.i.a.

(8) Open valve 85 and discharge coal from lock-hopper 83 at about 35 p.s.i.a. As coal is discharged, air at about 35 p.s.i.a. flows from surge-chamber 88 into lock-hopper 83 to fill space made empty by discharge of coal.

(9) When lock-hopper 83 is empty, close valves 85 and 98, and open valve 99, pressuring lock-hopper 83 to about 64 p.s.i.a. from surge-chamber 89.

(10) Close valve 99 and open valve 100, pressuring lock-hopper 83 to about 116 p.s.i.a. from surge-chamber 90.

(11) Close valve 100 and open valve 101, pressuring lock-hopper 83 to about 212 p.s.i.a. from surge-chamber 91.

(12) Close valve 101 and open valve 102, pressuring lock-hopper 83 to about 385 p.s.i.a. from surge-chamber 92.

(13) Close valves 102 and 96 and open valve 93, pressuring lock-hopper 83 to about 700 p.s.i.a. from floating header 42. Lock-hopper 83 is now ready to receive coal at 700 p.s.i.a. from terminal end 67', viz., valve 81 may be opened when lock-hopper 84 is full of coal.

The operating pressure levels in surge-chambers 88 through 92 are not arbitrary. I have discovered that the above-described arrangement and operating procedure leads automatically, in absence of any control devices or means not mentioned here, to a particular series of pressure levels in the several surge-chambers. The pressure in surge-chamber 92 is such that the air density in the chamber is just equal to the density of 700-p.s.i.a. air times the fraction of the volume of a coal-filled lock-hopper which is occupied by air. I have taken this fraction as 0.55 and assumed ideal-gas densities of air in obtaining the approximate pressure 385 p.s.i.a. for surge-chamber 92. Similarly, the density of air in surge-chamber 91 is the same fraction times the density of air in surge-chamber 92. And so forth. Thus, the coal-delivery pressure of 35 p.s.i.a. is not arbitrary, but is a consequence of the choice of 700 p.s.i.a. as the level in floating header 42 and of the fact that five surge-chambers 88 through 92, each much larger than a lock-hopper, have been provided at the delivery station. It will be recognized that the delivery station could be modified to afford a delivery pressure other than 35 p.s.i.a.

The beauty of the design of the delivery station lies in its ability to recover air in coal at 700 p.s.i.a., transferring this air to floating header 42, simply at the cost of compressing a relatively small quantity of air from the atmosphere to 35 p.s.i.a. This small quantity of air corresponds almost exactly to the air which leaves the system along with coal delivered at 35 p.s.i.a. Exact correspondence is achieved only if surge-chambers 88 through 92 and floating header 42 are "infinitely" big, but the limit can be closely realized in practice.

For purpose of illustration, the foregoing example predicates an average pressure gradient of 5 p.s.i. per mile along the coal-conveying duct. The example locates stations for bleed-off of segregated gas at a "standard" interval of one-eighth mile, and locates pumping stations at a "standard" interval of 60 miles. In actual practice, the pressure gradient will vary, above and below 5 p.s.i. per mile, according to the lay of the ground to be traversed. For example, if a steep hill must be climbed, the pressure gradient will be higher. On the other hand, pressure gradients in down-hill stretches can be small. Intervals between bleed-off and pumping stations will in practice vary above and below the "standard" intervals used in the example.

The total horsepower requirements for conveying coal across a given distance depends of course upon the exact lay of the land. If an average pressure gradient of 5 p.s.i. per mile can be maintained, so that the foregoing "standard" intervals may be used on the average—and also if the various surge-chambers and floating header 42 are extremely large in comparison with the various lock-hoppers—I find that the total brake-horsepower for air compression is given approximately by the formula: $4,000 + 6,700N$, where N = number of 60-mile segments of duct. For example, if the duct is 1200 miles long (having 19 pumping stations), the total brake-horsepower is 138,000. This works out to a power requirement of about 90 kilowatt-hours per ton of coal delivered across a distance of 1200 miles, an outstandingly low value. Power for a practical system, worked out for a given situation having both up-hill and down-hill portions of duct and having surge-chambers of practicable size, should not be much more than this.

Construction of a bleed-off station may be simplified, without incurring a drastic increase in total power re-

quirement, if control valve 66 and connection from filter 63 to header 42 are omitted. If this is done, the volumetric flow of air available for use as emulsifying air increases as one proceeds along a given 60-mile segment of duct, and, advantageously, the distance between bleed-off stations should correspondingly be increased and beyond one-eighth mile. The pressure boost in blower 65 should also be increased, because the pressure drop from one bleed-off station to the next gradually becomes larger. At intervals along the 60-mile segment—for example, every 5 or 10 miles, say—a bleed-off station could advantageously be provided with control valve 66 and connection from filter 63 to header 42. In such a station, the function and object of control valve 66 would be to pass a quantity of air to header 42 such that the volumetric flow of air proceeding to the next blower 65 is reduced approximately to the volumetric flow through blower 45, at the beginning of the 60-mile segment.

A further simplification of at least some of the bleed-off stations is possible if gas removed via line 60 at a given bleed-off station is used, without any boost in pressure, as emulsifying gas to a section of duct sufficiently far downstream that the pressure level in coal mass 6 is approximately 2 or more p.s.i. below the pressure level at the given bleed-off station.

Those skilled in the art will recognize alternate designs suitable for separation of air from coal at a bleed-off station. To cite an example, the entire mass of coal and air arriving at a bleed-off station might be fed directly to a cyclone-separator designed to handle gas at high solids loading. Several cyclone stages in series might be provided.

The functioning of floating header 42 may be aided by providing optional surge-chamber 103, receiving air from optional blower 104, both placed in floating header 42 at a point near the charging station. In similar fashion, the functioning of floating header 42 may be aided by providing optional surge-chamber 105, receiving air from optional blower 106, both placed in floating header 42 at a point downstream from and nearby each pumping station. Further, optional surge-chamber 107 may advantageously be placed in floating header 42 at a point upstream from and nearby the delivery station.

The specific embodiment shown in FIGS. 1 and 2 and described above is for illustrative purposes only, and is not intended to limit my invention. Those skilled in the art will recognize ways of using a gas other than air, such as natural gas for example, which might be available at a high pressure and which one might wish to convey between approximately the same terminal locations as the coal or other solid conveyed. An artificial gas produced from coal might advantageously be used. In some situations there may be advantage in using gas-turbine power plant to drive one or more of the air compressors, and in such situations air to the gas turbine may advantageously be drawn from one or more of the surge-chambers shown in FIG. 2.

The scope of my invention is embraced in the following claims.

I claim:

1. Apparatus for the conveying of a pulverulent solid in a generally horizontal direction by action of a gasiform fluid, comprising: an enclosed duct substantially free of transverse obstructions and having a bottom a fractional portion of which is porous, means for admitting said fluid through said porous portion at a vertically upward velocity higher than the minimum buoyancy velocity of said solid, said porous portion forming a proportion to said bottom to create a pressure gradient at substantially every given part of said duct which is substantially the same as the pressure gradient of a hypothetical two-phase mixture of said gasiform fluid with a liquiform fluid having a density equal to the loosest settled density of said solid and having a viscosity in the order of 1 centipoise, said hypothetical mixture flowing through a duct of non-porous

walls congruent with said duct at the same mass rate as the true mixture of solid and gasiform fluid at said given part of said duct, said hypothetical two-phase mixture containing said liquiform and gasiform fluids in relative weight proportions determined from the true flowing mixture of said solid and said gasiform fluid, the determination of said relative weight proportions taking said solid at said density and counting only the non-interstitial fraction of said gasiform fluid, and means for charging said solid into said duct at an inlet end and withdrawing same from an outlet end at a rate such that the flow of said hypothetical two-phase mixture in said congruent duct is characterized by a Reynolds Number greater than 2000 and hence is in the turbulent regime.

2. Apparatus for the conveying of a pulverulent solid in a generally horizontal direction by action of a gas, comprising: an enclosed duct substantially free of transverse obstructions and having a bottom a fractional portion of which is porous; means for admitting a gas through said porous portion at a vertically upward velocity higher than the minimum buoyancy velocity of said solid, said porous portion forming a proportion to said bottom to create a pressure gradient at substantially every given horizontal part of said duct which is substantially that which is calculated from the formula

$$\frac{\Delta P}{L} = \frac{2f(W/A)^2}{32.2D\rho_s S^{0.87}} \times \frac{5280}{144}$$

and means for charging said solid into said duct at an inlet end and withdrawing same at an outlet end at a rate such that Reynolds Number Re is greater than 2,000; wherein: $\Delta P/L$ =pressure gradient in p.s.i. per mile; $W=W_s+W_g$; W_s and W_g =mass flow of said solid and said gas in pounds per second respectively along said duct at said given horizontal part; A =cross-sectional area of said duct in square feet; D =equivalent diameter of said duct in feet; ρ_s =loosest settled density of said solid in pounds per cubic foot;

$$S = \frac{W_s/\rho_s}{(W_g/\rho_g) + W_s(1-\epsilon)/\rho_s}$$

ρ_g =density of said gas in pounds per cubic foot; ϵ =fraction of volume of said solid which is occupied by interstitial gas when said solid is at its loosest settled density ρ_s ; f =friction factor determined from known correlations of friction factor versus Re for homogeneous fluid flow through a smooth-walled pipe of diameter D ; and $Re=DW/0.000672A$.

3. Apparatus for the conveying of a pulverulent solid in a generally horizontal direction by action of a gas at an elevated pressure, comprising: an enclosed duct substantially free of transverse obstructions, means for charging said solid at a given rate into said duct at an inlet end and withdrawing same from an outlet end, means for supplying emulsifying gas into said duct through the underside of said duct at a portion thereof and at a rate such that said emulsifying gas maintains said solid in the state of a gas-solid emulsion having liquid-like properties at substantially every point within said duct, said action being reflected by a pressure gradient at substantially every point along said duct not less than the pressure gradient prevailing in a liquid when said liquid is caused to flow through an enclosed duct congruent with said duct at said given rate, said liquid having a density equal to the loosest settled density of said solid and having a viscosity in the order of 1 centipoise, and said given rate being such that said liquid flow is characterized by a Reynolds Number greater than 2000 and hence is turbulent.

4. Apparatus for the cross-country conveying of a pulverulent solid as set forth in claim 3 which comprises: a series of apparatuses of claim 3 disposed so that the outlet end of a given member of said series is substantially contiguous with the inlet end of the next succeeding member, and including means for separating gas from solid at the outlet end of each given member of said series, means for feeding solid into the next succeeding member, and means for supplying at least a portion of said separated gas to an available succeeding member of said series, if any, to serve as emulsifying gas therein.

5. Apparatus for the cross-country conveying of a pulverulent solid by action of a gas, said solid moving in a liquid-like state displaying liquid-like turbulence, said apparatus comprising: a series of enclosed ducts each substantially free of transverse obstructions and each having an inlet end and an outlet end, said series being disposed so that the outlet end of a given member of said series is substantially contiguous with the inlet end of the next succeeding member; means for charging said solid into the inlet end of each given member of said series and for discharging solid from the outlet end of each member at not less than a given rate; means for supplying emulsifying gas into each given duct of said series through the underside of said given duct at a portion thereof and at a rate and in a manner so that said emulsifying gas cooperates with said turbulence to maintain said solid in a liquid-like state at substantially every point within said duct, said turbulence being insured by said given rate and the maintenance of said liquid-like state, said action being reflected by a substantial pressure gradient along each said given duct; said given rate being such that the flow of water at the same rate through an enclosed duct congruent with each given member of said series is characterized by a Reynolds Number greater than 2000 and hence is turbulent; means for separating gas from solid at the outlet end of each given member of said series; and means for supplying at least a portion of said separated gas to an available succeeding member of said series, if any, to serve as emulsifying gas therein.

6. Apparatus for the cross-country conveying of a pulverulent solid by action of a gas at elevated pressure, said solid moving in a liquid-like state displaying liquid-like turbulence, said apparatus comprising: a series of enclosed ducts each having an inlet end and an outlet end, said series being disposed so that the outlet end of a given member of said series is substantially contiguous with the inlet end of the next succeeding member; means for charging said solid into the inlet end of each given member of said series and for discharging solid from the outlet end of each member at not less than a given rate; means for supplying emulsifying gas into each given duct of said series through the underside of said given duct at a rate and in a manner so that said emulsifying gas cooperates with said turbulence to maintain said solid in a liquid-like state at substantially every point within said duct, said turbulence being insured by said given rate and the maintenance of said liquid-like state, said action being reflected by a substantial pressure gradient along each said given duct and said elevated pressure declining through said series from an initial pressure at the inlet end of the first duct of said series to a final pressure at the outlet end of the last duct of said series; means for separating gas from solid at the outlet end of each given member of said series; means for supplying at least a portion of said separated gas to an available succeeding member of said series, if any, to serve as emulsifying gas therein; a parallel pipe carrying said gas in absence of said solid at an elevated pressure not greater than said final pressure; and means for discharging said separated gas from the outlet end of the final member of said series into said parallel pipe.

7. Apparatus of claim 6 including: means cooperating with each of said means for separating gas at the outlet

end of each given duct of said series to cause a minor portion of said separated gas to flow into said parallel pipe, said minor portion corresponding substantially to the increase in volume of the total gas entering said given duct either with solid or as emulsifying gas.

8. Apparatus of claim 6 including: means cooperating with at least some of said means for separating gas at the outlet end of a given duct of said series to cause a portion of said separated gas to flow into said parallel pipe, said portion corresponding substantially to the increase in volume of the total gas arriving at said outlet end of said given duct by comparison with the volume of the total gas arriving at the outlet end of the first duct of said series.

9. Apparatus of claim 6 including: gas-compression means connected with said parallel pipe to supply at least a portion of gas needed to raise the pressure of said solid to said initial pressure to permit feed of solid to the inlet end of the first duct of said series.

10. Apparatus of claim 6 including: means cooperating with at least some of said means for separating gas at the outlet end of a given duct of said series to cause a portion of said separated gas to flow into said parallel pipe; and gas-compression means connected with said parallel pipe to supply at least a portion of gas needed to raise the pressure of said solid to said initial pressure to permit feed of solid to the inlet end of the first duct of said series.

11. Apparatus for the cross-country conveying of a pulverulent solid as set forth in claim 6 which comprises: a series of two apparatuses of claim 6 disposed so that the outlet end of the last member of said series of ducts of the first of said apparatuses is substantially contiguous with the inlet end of the first member of said series of ducts of the second of said apparatuses; at least two lock-hoppers situated to receive solids from said outlet end and to deliver solids into said inlet end; a connection and an on-off valve interposed between each given lock-hopper and said outlet end, controlling flow of said solid into said given lock-hopper; a connection and an on-off valve interposed between each given lock-hopper and said inlet end, controlling flow of said solid from said lock-hopper into said inlet end; a valved connection between each given lock-hopper and said parallel pipe; a valved connection between each given lock-hopper and a surge-chamber, large with respect to each lock-hopper, containing gas at a pressure higher than said elevated pressure prevailing in said parallel pipe and continuously supplied with said gas by gas-compression means connected with said parallel pipe; and means for supplying emulsifying gas from said surge-chamber to at least the first member of said series of ducts in said second apparatus of claim 6.

12. Apparatus of claim 6 including: at least two lock-hoppers situated to receive solids from the outlet end of the final member of said series; a connection and an on-off valve interposed between each given lock-hopper and said outlet end, controlling flow of said solid into said given lock-hopper; a connection and an on-off valve interposed between each given lock-hopper and means for delivering solid at a pressure substantially below said elevated pressure prevailing in said parallel pipe; a valved connection between each given lock-hopper and said parallel pipe; a valved connection between each given lock-hopper and a header; valved branch connections between said header and surge-chambers isolated from one another and containing gas at a series of pressures progressively below said elevated pressure prevailing in said parallel pipe, each of said surge-chambers being large with respect to each lock-hopper; means for supplying gas continuously to the surge-chamber at the lowest pressure of said series, said pressure being substantially the pressure of said means for delivering solid; and gas-compression means connected with said parallel pipe supplying at least a portion of gas needed to raise the pressure of said solid to said initial pressure.

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13. Method of conveying pulverulent solid in a substantially horizontal direction through the action of a gas through an enclosed duct substantially free of transverse obstructions and having a bottom a fractional portion of which is porous, said method comprising: applying an elevated pressure at the inlet end of said duct and feeding said solid to said end at not less than a given rate; causing emulsifying gas to flow through said portion of said bottom at a velocity higher than the minimum buoyancy velocity of said solid and at a rate sufficient to maintain said solid in a liquid-like state when said emulsifying gas acts in cooperation with a liquid-like turbulence insured by said given rate and the existence of said liquid-like state; said action being reflected by a pressure gradient at substantially every point along said duct not less than the pressure gradient prevailing in a liquid when said liquid is caused to flow through an enclosed duct congruent with said duct at said given rate, said liquid having a density equal to the loosest settled density of said solid and having a viscosity in the order of 1 centipoise, and said given rate being such that said liquid flow is characterized by a Reynolds Number greater than 2000 and hence is turbulent.

14. Method of conveying a pulverulent solid in a generally horizontal direction by action of a gasiform fluid which comprises: providing an enclosed duct substantially free of transverse obstructions and having a bottom a fractional portion of which is porous, said porous portion forming a proportion to said bottom to create a pressure gradient at substantially every given part of said duct which is substantially the same as the pressure gradient of a hypothetical two-phase mixture of said gasiform fluid with a liquiform fluid having a density equal to the loosest settled density of said solid and having a viscosity in the order of 1 centipoise, said hypothetical mixture flowing through a duct of non-porous walls congruent with said duct at the same mass rate as the true mixture of solid and gasiform fluid at said given part of said duct, said hypothetical two-phase mixture containing said liquiform and gasiform fluids in relative weight proportions determined from the true flowing mixture of said solid and said gasiform fluid, the determination of said relative weight proportions taking said solid at said density and counting only the non-interstitial fraction of said gasiform fluid; admitting said gasiform fluid through said porous portion of said bottom at a vertically upward velocity higher than the minimum buoyancy velocity of said solid; and charging said solid into said duct at an inlet end and withdrawing same from an outlet end at a rate such that the flow of said hypothetical two-phase mixture in said congruent duct is characterized by a Reynolds Number greater than 2000 and hence is in the turbulent regime.

15. Method of conveying a pulverulent solid in a general horizontal direction by action of a gas which comprises: providing an enclosed duct substantially free of transverse obstructions and having a bottom a fractional portion of which is porous, said porous portion forming a proportion to said bottom to create a pressure gradient at substantially every given horizontal part of said duct which is substantially that which is calculated from the formula

$$\frac{\Delta P}{L} = \frac{2f(W/A)^2}{32.2D\rho_s S^{0.57}} \times \frac{5280}{144}$$

admitting a gas through said porous portion at a vertically upward velocity higher than the minimum buoyancy velocity of said solid; and charging said solid into said duct at an inlet end and withdrawing same at an outlet end at a rate such that Reynolds Number Re is greater than 2000; wherein: $\Delta P/L$ =pressure gradient in p.s.i. per mile;

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said duct in square feet; D =equivalent diameter of said duct in feet; ρ_s =loosest settled density of said duct in square feet; D =equivalent diameter of said duct in feet; ρ_s =loosest settled density of said solid in pounds per cubic foot;

$$S = \frac{W_s/\rho_s}{(W_g/\rho_g) + W_s(1 - \epsilon)/\rho_s}$$

ρ_g =density of said gas in pounds per cubic foot; ϵ =fraction of volume of said solid which is occupied by interstitial gas when said solid is at its loosest settled density ρ_s ; f =friction factor determined from known correlations of friction factor versus Re for homogeneous fluid flow through a smooth-walled pipe of diameter D ; and $Re=DW/0.000672A$.

16. Method of cross-country conveying of a pulverulent solid by action of a gas, said solid moving in a liquid-like state displaying liquid-like turbulence through a series of enclosed ducts each substantially free of transverse obstructions and each having an inlet end and an outlet end, said series being disposed so that the outlet end of a given member of said series is substantially contiguous with the inlet end of the next succeeding member, and said action being reflected by a substantial pressure gradient along each said given duct, said method comprising: charging said solid into the inlet end of each given member of said series and discharging solid from the outlet end of each member at not less than a given rate; supplying emulsifying gas into each given duct of said series through the underside of said given duct at a portion thereof and at a rate and in a manner so that said emulsifying gas cooperates with said turbulence to maintain said solid in a liquid-like state at substantially every point within said duct, said turbulence being insured by said given rate and the maintenance of said liquid-like state; said given rate being such that the flow of water at the same rate through an enclosed duct congruent with each given member of said series is characterized by a Reynolds Number greater than 2000 and hence is turbulent; separating gas from solid at the outlet end of each given member of said series; and supplying at least a portion of said separated gas to an available succeeding member of said series, if any, to serve as emulsifying gas therein.

17. Method of cross-country conveying of a pulverulent solid by action of a gas at elevated pressure, comprising: moving said solid in a liquid-like state displaying liquid-like turbulence through a series of enclosed ducts each having an inlet end and an outlet end, said series being disposed so that the outlet end of a given member of said series is substantially contiguous with the inlet end of the next succeeding member, said action being reflected by a substantial pressure gradient along each said given duct and said elevated pressure declining through said series from an initial pressure at the inlet end of the first duct of said series to a final pressure at the outlet end of the last duct of said series, said series being paralleled by a pipe carrying said gas in absence of said solid at an elevated pressure not greater than said final pressure; charging said solid into the inlet end of each given member of said series and discharging solid from the outlet end of each member at not less than a given rate; supplying emulsifying gas into each given duct of said series through the underside of said given duct at a rate and in a manner so that said emulsifying gas cooperates with said turbulence to maintain said solid in a liquid-like state at substantially every point within said duct, said turbulence being insured by said given rate and the maintenance of said liquid-like state; separating gas from solid at the outlet of each given member of said

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series; supplying at least a portion of said separated gas to an available succeeding member of said series, if any, to serve as emulsifying gas therein; and discharging said separated gas from the outlet end of the final member of said series into said paralleling pipe.

18. The method of claim 17 including: causing gas to flow through said paralleling pipe toward the inlet end of the first member of said series, and using said gas as at least a portion of gas needed to raise the pressure of said solid to said initial pressure.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,268,264

August 23, 1966

Arthur M. Squires

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 2, line 69, for "variable" read -- variables --; column 4, line 58, for " $\Delta P/L$ " read -- $\Delta P/L$ --; column 6, line 26, after "-gas" insert -- pad --; column 13, line 6, strike "and"; column 14, line 29, after the formula for " $\Delta P/L$ " insert a semicolon; line 45, after the formula for "S" insert a semicolon; column 17, line 66 after the formula " $\Delta P/L$ " insert a semicolon; column 18, lines 1 and 2, strike out "said duct in square feet; D=equivalent diameter of said duct in feet; ρ_s =loosest settled density of", and insert instead -- $W=W_s+W_g$; W_s and W_g =mass flow of said solid and said gas in pounds per second respectively along said duct at said given horizontal part; A=cross-sectional area of --; column 18, line 9, after the formula for "S", insert a semicolon; line 14, for "e" read -- ϵ --.

Signed and sealed this 5th day of September 1967.

(SEAL)

Attest:

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