

Dec. 16, 1969

R. E. ROSENSWEIG

3,483,969

MATERIAL SEPARATION USING FERROMAGNETIC LIQUID TECHNIQUES

Filed July 5, 1967

FIG. 1.

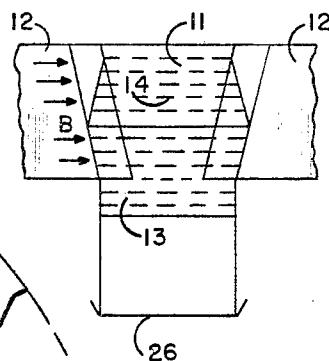
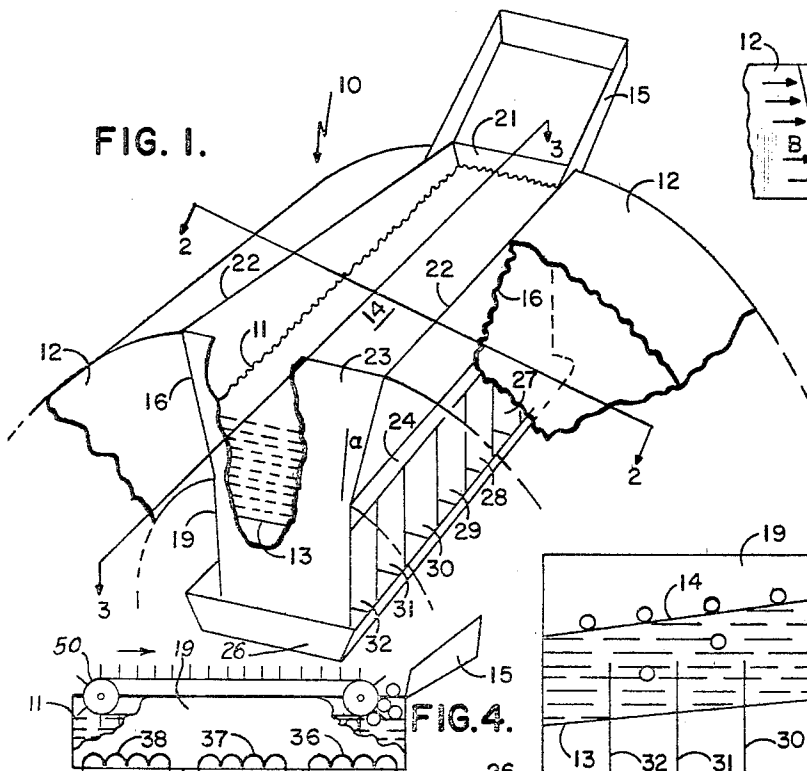


FIG. 2.

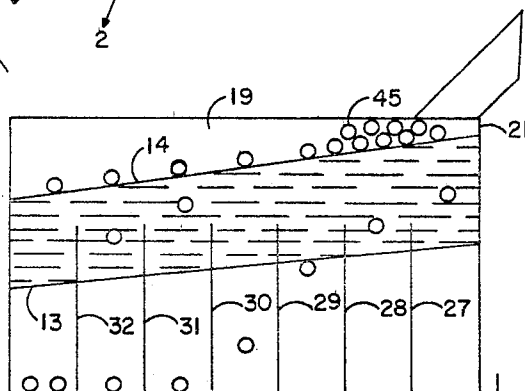


FIG. 3.

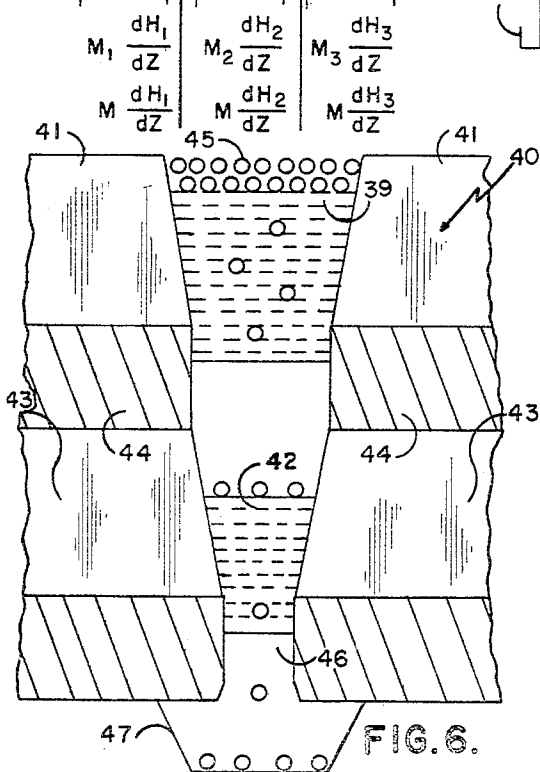


FIG. 4.

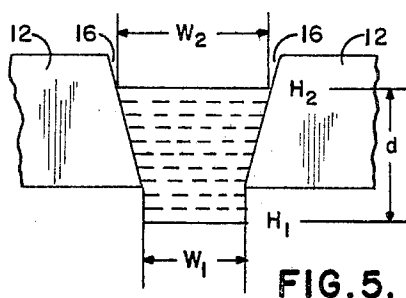


FIG. 5.

RONALD E. ROSENSWEIG
INVENTOR

BY *Charles H. Hogan*
Albert G. Gorman

1

3,483,969

MATERIAL SEPARATION USING FERROMAGNETIC LIQUID TECHNIQUES

Ronald E. Rosensweig, Lexington, Mass., assignor to Avco Corporation, Cincinnati, Ohio, a corporation of Delaware

Filed July 5, 1967, Ser. No. 651,294

Int. Cl. B03c 1/00; B03b 13/04

U.S. Cl. 209—1

17 Claims

ABSTRACT OF THE DISCLOSURE

Apparatus and method of separating materials of different density. A controlled magnetic field is passed through a ferrofluid. The materials introduced thereinto distribute themselves in accordance with their densities.

A continuous separation process is described. A magnetic sieve approach is used whereby the field intensity and magnetic field gradient is varied in a predetermined distribution thus creating a non-uniform distribution of levitation forces. The levitation forces vary from a maximum to a minimum thus providing means for discriminating between materials of different density as a function of density.

DEFINITIONS

For the purposes of this discussion, a ferrofluid is defined as a material comprising a permanent suspension of ferromagnetic material in a liquid carrier. The ferromagnetic material does not separate from the liquid carrier in the presence of a magnetic, gravitational, or acceleration field. The composite which is comprised of carrier fluid and particles appears to have the property of magnetic polarizability that is uniform.

For the purposes of this discussion, levitation shall be understood to mean the effect of raising a body in contact with or submersed in ferrofluid in a direction opposite to gravity.

Non-magnetic material is defined as material of magnetization less than the magnetization of the ferrofluid used.

Additional information relating to the subject matter of this invention may be found in the co-pending application entitled, "Means for and Method of Moving Objects by Ferrohydrodynamics," Ser. No. 487,520, filed Sept. 15, 1965, and/or the article entitled, "Magnetic Fluids," by R. E. Rosensweig (International Science and Technology, July 1966).

BACKGROUND OF THE INVENTION

In general, this invention is directed to a process of separating material of different density and more particularly to accomplishing on a continuous basis this objective through the use of magnetic fields and ferrofluids.

OBJECTS

It is an object of the invention to provide a novel method of separating materials in a continuous process according to the difference in density of the materials.

It is another object of the invention to provide a process for separating materials according to their respective densities on a continuous basis using the interaction of magnetic fields and ferrofluids.

It is yet another object of the invention to achieve separation of material of different density by sequential levitation whereby materials of different density are segregated out of a mixed mass of materials in sequence according to their respective densities.

It is yet another object of the invention to achieve separation of materials of different density on a continuous basis irrespective of the shape and size of the material.

2

It is still another object of the invention to described an apparatus for achieving continuous separation of materials as a function of the density of the material utilizing the interaction of the magnetic field and ferrofluid.

It is still another object of the invention to describe a process for and an apparatus for achieving continuous separation of materials utilizing ferrofluids and requiring no flow or circulation of ferrofluid.

The invention both as to its organization and method of operation, together with additional objects and advantages thereof, will best be understood from the following description of a specific embodiment when read in conjunction with the accompanying drawings, in which:

FIGURE 1 is a perspective drawing of an apparatus embodying the principles of the invention.

FIGURE 2 is a section taken along lines 2—2 in FIGURE 1.

FIGURE 3 is a section taken along lines 3—3 in FIGURE 1.

FIGURE 4 is a schematic representation illustrating an alternate construction of the FIGURE 1 apparatus.

FIGURE 5 is a schematic representation illustrating the relationship between an analytical equation and a physical effect.

FIGURE 6 is a simplified and preferred embodiment of the inventive concept.

GENERAL THEORY OF OPERATION

The purpose of this invention is to separate materials of different density using the principle of levitation in a ferrofluid. While the process and theory will be discussed in terms of solid particles, the process will work with immiscible liquids of different density.

The following equation was developed from the force equation presented in the co-pending patent applications identified above. It describes the equilibrium gravitational and magnetic forces acting on a non-magnetic object in a ferrofluid in the presence of a magnetic field having a vertical gradient.

$$(\rho_s - \rho_L)g = \frac{M}{4\pi} \frac{dH}{dZ} \quad (\text{Equation 1})$$

In the above equation:

ρ_s = density of the solid, gr./cm.³

ρ_L = density of the liquid, gr./cm.³

g = acceleration of gravity = 981 cm./sec.²

M = average magnetization of liquid displaced by solid particle, gauss

dH/dZ = magnitude of the gradient of magnetic field oersted/cm.

The gravitational term in Equation 1 (the left-hand term) is determined only by the difference in density of the solid object being levitated and density of ferrofluid used. For any given system both of these parameters are known. The magnetic (right-hand) term of Equation 1 is determined at least by the height, Z , above an arbitrary reference line. Since H is also a function of Z so is dH a function of Z . For a given ferrofluid, the magnetization of the liquid, M , is determined by the local field H , so it too, is solely a function of Z .

In practice, it is important to recognize that there are two specific requirements for the magnetic field. First, it must be strong enough to result in a noticeable magnetization of the fluid and secondly, the magnitude of this field must decrease in the vertical direction so as to create a vertical gradient dH/dZ .

It would appear when a mixture of solid objects of different density is immersed in a ferrofluid and such a magnetic field applied, each of these solid objects—or non-magnetic immiscible fluids—of different density can be selectively levitated. At least two situations have become

clear. If dH is uniform throughout the ferrofluid, the levitation forces increase with an increase in MdH/dZ . If M is a saturation value, then the levitation force is purely a function of dH/dZ . Accordingly, as dH/dZ is increased, objects of lowest density will be levitated first to be followed in a sequence by objects of greater density in order of their relative densities.

A limitation is that the materials to be separated are non-magnetic. The magnetic levitation effect will be smaller with solid objects that are magnetically responsive than with magnetically non-responsive materials. Magnetically responsive solids will behave as non-magnetic objects of higher density. The magnetic lift term will be equal

$$\frac{1}{4\pi}(M - M_s) \frac{dH}{dZ}$$

where M_s is the volume average magnetization of the solid. When $M_s=0$, this reduces to Equation 1. When $M_s \geq M$, there is no magnetic levitation effect possible. The presence of strongly magnetic substances (i.e., $M_s > M$) in the batch of materials to be separated has very little deleterious effect on the process described since the material will be attracted to the magnetic field and made an inactive constituent.

DESCRIPTION AND OPERATION

Referring to FIGURE 1 there is depicted an apparatus generally designated 10 for separating substantially non-magnetic materials of different density from a mixture of such materials. The apparatus 10 includes a chute 15 in which a mixture of materials having different density is placed. The chute 15 includes an inclined surface 17 for directing the mixture of material into a channel 19.

The channel 19 is situated in the air gap of a magnet identified through magnet pole pieces 12. The pole faces 16 of the pole pieces 12 are inclined to the vertical by an angle α . The inclination is provided, primarily, to form a magnetic gradient dH/dZ . The pole pieces 12 also diverge horizontally for reasons to be explained later.

The channel 19 as depicted is a bottomless trough. In the alternative it may be a conventional trough 19 having a bottom or it may be a completely enclosed channel. These features do not effect the operation of the apparatus.

The trough 19 is non-magnetic and includes an inlet 21 and a pair of walls 22 oriented to conform to the slopes of the pole faces 16. This orientation is obviously not required.

Directly below the trough 19 is a pan 26 containing a plurality of vertical partitions 27 through 32 which as seen in FIGURE 3 extend from the pan 26 to the vertical extensions 24 and into the trough 19. A body of ferrofluid 11 is contained in the trough 19. The top surface 14 is seen to slant downward from the inlet 21 to the remote end 23. The depth "d" of the ferrofluid 11 is determined by an analytical relationship which will be described hereinafter. The ferrofluid 11 is maintained in position within the bottomless trough 19 by a magnetic field passing through the magnetic fluid as indicated figuratively by the arrow B (lines/in.²). The magnetic field is provided by means of a pair of pole pieces 12. A portion of one pole piece 12 is broken away in order not to obscure the structural details of the trough described heretofore. The source of the magnetic field is not shown. It may either be a coil of wire wrapped around a ferromagnetic material from which the pole pieces 12 are constructed, or, in the alternative, the pole pieces may be part of a permanent magnet.

SPECIFIC THEORY OF OPERATION: (FIGURE 5)

Referring to FIGURE 5 of the drawings, there is depicted a schematic representation of ferrofluid 11 held in place in space by a magnetic field M generated by a magnet represented by pole pieces 12.

Ferrofluid when placed between pole pieces of a magnet as illustrated in FIGURE 5 will attempt to line up

and bridge the gap separating pole pieces just as any other magnetic material tends to do. It is seen that the bottom surface 13 of the ferrofluid 11 extends below the pole pieces 12 while the top surface 14 of the ferrofluid is situated below the top surface of the pole piece. The position assumed by the magnetic field will vary with its own properties and the characteristics of the magnetic field. The depth of the ferrofluid 11 is determined by the relationship:

$$d = \frac{1}{4\pi\rho g} \int_{H_1}^{H_2} M dH \quad (\text{Equation 2})$$

In this case dH is formed by the non-parallel pole faces 16. The difference in gap length creates a difference in magnetic field intensity in the gap in a vertical direction.

Assuming constancy of the magnetomotive force the diverging pole faces 16 in FIGURE 5 creates a magnetomotive force H_1 in the gap at the bottom of the ferrofluid 11 where the pole pieces 12 are separated by the distance W_1 . Where the opposing surfaces of the pole faces 16 are separated even further apart at W_2 , at the top surface of the ferrofluid 11, a magnetomotive force H_2 is created. The value of H_1 can be approximately regarded as zero. The value of H_2 is given as a consequence of electromagnetic theory from the relationship

$$\nabla \times \vec{H} = \vec{j}$$

where ∇ is the conventional vector operator $\vec{H}$ is the vector quantity of electromagnetic force and $\vec{j}$ is the vector quantity of current associated with $\vec{H}$, as

$$H_2 W_2 = KNI$$

where K is a constant greater than 1, N is the number of turns of conductor carrying the current I which energizes the magnet and W the width of the channel.

THEORY APPLIED TO FIGURE 1

It is clear from the foregoing that the H at the surface of the ferrofluid 11 at inlet 21 is greater than H' at the surface of the ferrofluid 11 at the remote end 23. Thus the depth of ferrofluid 11 at the inlet 21 is greater than the depth of ferrofluid 11 at the remote end 23. The structural result is an inclined free top surface 14 which is important to the operation as will be explained hereinafter and in general an inclined bottom surface 13 which, however, is not important to the operation. (See FIGURE 3.)

When a ferrofluid and a magnetic field interact, there is conferred on the ferrofluid an increase in density. The magnitude of the apparent density is described by the following relationship:

$$(\text{Density})_{\text{apparent}} = \rho_L + \frac{M}{4\pi g} \frac{dH}{dZ} \quad (\text{Equation 3})$$

This apparent density is uniform over any vertical plane providing MdH/dZ is constant over the plane. This condition is achieved by matching the pole pieces geometry to the ferromagnetic fluid BH characteristic in the vertical plane. The BH characteristic is a curve of flux density, B , as a function of magnetic field density, H . It is also commonly referred to as a magnetization curve. The ability of the ferrofluid and magnetic field to levitate a nonmagnetic object stems from the apparent change in density of the fluid. Where the apparent density is greater than the actual density of a nonmagnetic material in contact with the fluid, the latter will float to the surface. The converse is also true.

The trough 19 diverges so that it is wider at the remote end 23 than it is at the inlet 21. This produces a monotonically increasing value of MdH/dZ and hence an increasing value of apparent density in the direction toward the inlet 21.

As a result of arrangement described above if a feed mixture is introduced at the inlet 21, all, or all but the most dense components of the mixture may be floated at the top surface 14 at the point of introduction, inlet 21. Then, due to the inclination of the top surface 14, the particles of the mixture will begin to float down the top surface 14 toward the remote end 23. In moving downward along the top surface 14 a point will come where, for one density component of the mixture, the apparent density of the fluid will be equal. At this point the components in question are on the verge of sinking and will do so upon moving a small distance further downstream. In this manner, graded components of the mixture will sink, will fall free of the fluid and be collected in the pan 26 between a pair of vertical partitions 27 through 32. The separation proceeds in a sequential fashion as the floating mixture proceeds downstream. The densest materials will deposit out of the ferrofluid at the inlet while the lowest density components will collect in the pan 26 under the remote end 23.

In FIGURE 4 there is a schematic representation of a separating apparatus in which the variation in magnetic field intensity and gradient is accomplished in steps rather than the continuous fashion previously described. This can be done in several ways including magnetic shunts of different dimensions bridging the gap between pole faces 16. However, this is shown symbolically by three separate and distinct magnetic field sources 36, 37 and 38. It is clear from the previous discussion that MdH/dZ is greatest at the inlet 21 and has the lowest magnitude at the remote end 23. The trough 19 is shown in a horizontal position with a uniform depth of ferrofluid 11. This is shown to illustrate that the sloped arrangement in FIGURE 1 is merely one embodiment and that the apparatus can function with a uniform depth of material. In this case any conventional technique or means such as the paddle belt 50 in FIGURE 4 is used to move the mixture of materials from the inlet 21 to the remote end 23.

Below also associated with the schematic in FIGURE 4 are two series of analytical terms. These are used to emphasize that levitation is a function of MdH/dZ . The top series of symbols are a general representation in which M_1 , M_2 and M_3 are not necessarily the same; so too dH_1 , dH_2 and dH_3 . The bottom series of terms represents a situation where the ferrofluid is saturated so that M is constant along the length of the trough 19 and the variation in levitation effect is accomplished through the inequality of dH_1 , dH_2 and dH_3 .

In FIGURE 6 there is depicted a ferrofluid material separator 40 which more nearly resembles the traditional concepts of a sieve. A mixture of materials 45 is fed to the material separator 40 and attempts to pass through the material separator due to the effects of gravity. Assuming a uniform apparent density in ferrofluids 39 and 42, the lightest density materials will be supported at the top of ferrofluid 39; any denser materials falls through ferrofluid 39 and the lightest portions of these are supported at the top of ferrofluid 42. The densest material falls through the ferrofluid 42 and is collected in pan 47. Although a two-stage separator is described, it is quite clear that any number of stages can be used.

In FIGURE 6 it is seen that a volume of ferrofluid 39 is retained between a pair of magnet pole pieces 41. The retention mechanism is the same as that which was previously described.

A second body of ferrofluid 42 is situated directly below the ferrofluid 39 by means of a second pair of magnetic pole pieces 43. The pole pieces 41 are physically separated by a non-magnetic spacer 44.

The apparent densities of ferrofluids 39 and 42 are adjusted, by adjusting the MdH/dZ imparted within the ferrofluids 39 and 42 by the magnetic field bridging each pair of pole pieces. The apparent densities of the ferrofluids 39 and 42 are adjusted so that ferrofluid 39 will

levitate light density materials and ferrofluid 42 slightly denser material.

In general, the material that is to be culled out of the mixture of materials and retained would be levitated by the ferrofluid 42, thus separating this particular material from components of the mixtures that are both less dense and more dense.

In detail, the operation of the material separator 40 is very simple and quite analogous to the conventional mechanical sieve. Materials 45 to be separated are introduced into the gap between pole pieces 41. Light components float on the surface of the ferrofluid 39. Others sink through the ferrofluid 39 to the ferrofluid 42. Material of predetermined density float on the surface of ferrofluid 42 while heavier components sink through the ferrofluid 42 and are removed via the outlet port 46 and pan 47. Material of predetermined density that is to be retained for further processing is removed from the surface of ferrofluid 42 in any convenient way.

In many ways the FIGURE 6 configuration is to be preferred and recommended over the FIGURE 1 configuration. It is simple in construction and operation. Through judicious adjustment of MdH/dZ it is possible to adjust the levitation effects of the ferrofluids 39 and 42 so that the apparatus as a whole will be able to discriminate between material of slightly different density. The FIGURE 6 configuration also offers the distinct ability to alter the levitation characteristics of the ferrofluids 39 and 42 independently to accommodate changes in the density makeup of the materials to be sorted.

GENERAL OBSERVATIONS

All apparatus concepts discussed heretofore lend themselves to high production rates and continuous operation. They require minimum amounts of ferrofluid and require minimum operator costs. The apparatus may be operated remotely or in a glove box thus minimizing loss of valuable material such as diamonds and other precious stones. The invention uses the properties of ferrofluid to the fullest advantage.

Note also that no ferrofluid need be moved or circulated. Collateral support equipment such as pumping and filtering apparatus are not needed.

As another important consideration, if the mixture of material is first treated with a ferrofluid repellent much in the same way as a garment is waterproofed, losses of ferrofluid can be materially reduced, if not eliminated. Several fluorocarbon compounds have been tested with very good results where water and kerosene are ferrofluid carriers. The concept however is not dependent on the use of a specific material since the liquid matrix used to make ferrofluids vary widely and a compatible repellent is required.

Additionally, the processes and apparatus described are not limited to separating solids. Globules of a mixture of liquids of different densities may be processed.

It is also clear that the ferrofluid 11 may be unloaded from between the pole faces of the magnet by merely removing the magnetic field. The ferrofluid will then drain. To recharge the apparatus it is only necessary to first energize the magnetic field and introduced ferrofluid into the gap between the pole faces of the magnet.

What is claimed is:

1. A process for separating substantially non-magnetic materials of different density comprising the steps of:
 - (a) providing an elongated channel having an inlet;
 - (b) filling said channel to a known depth with a ferrofluid material comprising a permanent colloidal suspension of magnetic material in a liquid carrier, which colloidal suspension does not separate from the liquid carrier in the presence of magnetic, gravitational or an acceleration field, of known density and magnetization;
 - (c) passing a magnetic field through said channel such that the field and ferromagnetic liquid produce a

force proportional to the term MdH/dZ opposite to gravity at each point along the length of the channel, the magnitude of MdH/dZ varying along the length of the channel from a maximum at the inlet to a minimum remote from the inlet;

- (d) supplying a mixture of particles of a substantially non-magnetic material of different density at the inlet, at least a portion of which is floated by the interaction of the magnetic field and ferrofluid; and
- (e) moving the mixture of material along the length of the channel away from the inlet whereby materials sink through the ferrofluid in the order of decreasing density.

2. A process as described in claim 1 wherein MdH/dZ varies continuously.

3. A process as described in claim 1 in which the ferrofluid is saturated by the magnetic field and dH/dZ varies with the length of the channel.

4. A process as described in claim 1 wherein MdH/dZ occurs in distinct steps.

5. A process as described in claim 1 wherein the mixture of material is moved along the length of the channel by means of gravity.

6. Means for separating substantially non-magnetic materials of different density comprising:

- (a) an elongated channel having an inlet and containing ferrofluid material comprising a permanent colloidal suspension of magnetic material in a liquid carrier, which colloidal suspension does not separate from the liquid carrier in the presence of magnetic, gravitational or an acceleration field, of known density and known depth;

- (b) means for passing a magnetic field through the channel, said magnetic field having a magnetic field intensity and gradient MdH/dZ in the direction of gravity, the magnitude of MdH/dZ varying along the length of the channel from a maximum at the inlet to a minimum remote from the inlet;

- (c) means for supplying a mixture of particles of a substantially non-magnetic material of different density to the inlet;

- (d) means for moving the mixture of material along the length of the channel away from the inlet whereby materials sink through the ferrofluid in the order of decreasing density; and

- (e) means situated below the ferrofluid for collecting material depositing out of the ferrofluid.

7. An apparatus as described in claim 6 in which the channel is a trough.

8. An apparatus as described in claim 6 in which the channel is a bottomless trough.

9. An apparatus as described in claim 6 in which the collecting means includes vertical spaces for selectively collecting components of the mixture according to density variations.

10. A process for separating substantially non-magnetic materials of different density comprising the steps of:

- (a) generating at least two magnetic regions each regions having a gradient dH/dZ in the direction of gravity where H is the magnetic field within the region and Z is a distance in the region opposite to the direction of gravity from a reference plane;

- (b) filling both of said regions with ferrofluid material comprising a permanent colloidal suspension of magnetic material in a liquid carrier, which colloidal suspension does not separate from the liquid carrier in the presence of magnetic gravitational or an acceleration field, such that MdH/dZ of a region is greater than MdH/dZ of another region where M is the average magnetization of the ferrofluid;

- (c) supplying a mixture of particles of a substantially non-magnetic material of different density to one of said regions such that at least a first portion of the material is levitated by the ferrofluid in said one

region, a second portion of the material sinks through the ferrofluid; and

- (d) moving either one of the first and second portions to said second region where a third portion of the material is levitated by the ferrofluid in said second region and a fourth portion sinks through the ferrofluid.

11. A process as described in claim 10 in which said levitated portions of said materials are carried in succession to each of said regions in order of decreasing MdH/dZ .

12. A process as described in claim 10 in which said levitated portions of said materials are carried in succession to each of said regions in order of increasing MdH/dZ .

13. Apparatus for separating substantially non-magnetic materials of different density comprising:

- (a) at least two regions of ferrofluid material comprising a permanent colloidal suspension of magnetic material in a liquid carrier, which colloidal suspension does not separate from the liquid carrier in the presence of magnetic, gravitational or an acceleration field;

- (b) means for generating in each region a gradient dH/dZ in the direction of gravity where H is the magnetic field within the region and Z is a distance in the region opposite to the direction of gravity from a reference plane such that MdH/dZ of one region is greater than MdH/dZ of another where M is the average magnetization of the ferrofluid of a region;

- (c) means for supplying a mixture of particles of a substantially non-magnetic material of different density to one of said regions such that at least a first portion of the material is levitated by the ferrofluid in one region, and a second portion of the material sinks through the ferrofluid;

- (d) means for moving either one of the first and second portions to said second region where a third portion of the material is levitated by the ferrofluid in said second region and a fourth portion sinks through the ferrofluid; and

- (e) means for collecting selected portions of said materials.

14. An apparatus as described in claim 13 in which said ferrofluid regions are laterally contiguous in decreasing order of MdH/dZ and said levitated portions of said mixture of materials is moved in succession to each region in the order of decreasing MdH/dZ .

15. An apparatus as described in claim 13 in which said ferrofluid regions are positioned one above the other in order of increasing magnitude of MdH/dZ in the direction of gravity and those portions of said mixture of materials that sink through a ferrofluid region are fed to a following region.

16. An apparatus for separating substantially non-magnetic materials of different density comprising:

- (a) means for supplying a magnetic field having a first gradient dH_1/dZ in the direction of gravity to an air gap defined by a pair of spaced magnetic pole pieces where H_1 is the magnetic field in the first air gap and Z is a distance in the first air gap opposite to the direction of gravity from a reference plane;

- (b) second means for supplying a magnetic field having a second gradient dH_2/dZ in the direction of gravity to a second air gap defined by a pair of second spaced magnetic pole pieces, said first air gap being positioned directly above the second air gap where H_2 is the magnetic field in the second air gap and Z is a distance in the second air gap opposite to the direction of gravity from a reference plane;

- (c) a quantity of first ferrofluid material comprising a permanent colloidal suspension of magnetic material in a liquid carrier, which colloidal suspension does not separate from the liquid carrier in the

presence of magnetic, gravitational or an acceleration field, of average magnetization M_1 in said first air gap;

- (d) a quantity of second ferrofluid material comprising a permanent colloidal suspension of magnetic material in a liquid carrier, which colloidal suspension does not separate from the liquid carrier in the presence of magnetic, gravitational or an acceleration field, of average magnetization M_2 in the second air gap, the product $M_1 dH_1/dZ$ being less than the product $M_2 dH_2/dZ$;
- (e) means for supplying a mixture of substantially non-magnetic material of different density to said first ferrofluid; and
- (f) means for collecting selected portions of said material that are levitated by and that sink through said first and second ferrofluids.

17. Means for separating substantially non-magnetic materials of different density comprising:

- (a) an elongated channel having an inlet and containing ferrofluid material comprising a permanent colloidal suspension of magnetic material in a liquid carrier, which colloidal suspension does not separate from the liquid carrier in the presence of magnetic, gravitational or an acceleration field, of known density and known depth, the width of the channel varies along its length from a minimum at the inlet to a maximum remote from the inlet;
- (b) means for passing a magnetic field through the channel, said magnetic field having a magnetic field intensity and gradient MdH/dZ in the direction of gravity, the magnitude of MdH/dZ varying along the length of the channel from a maximum at the inlet to a minimum remote from the inlet, the varying

magnetic field intensity in combination with the varying channel width creating a ferromagnetic liquid surface inclined downwardly from said inlet;

- (c) means for supplying a mixture of particles of a substantially nonmagnetic material of different density to the inlet; and
- (d) means situated below the ferrofluid for collecting material depositing out of the ferrofluid.

References Cited

UNITED STATES PATENTS

2,590,756	3/1952	Colin	209—208 X
2,902,153	9/1959	Green	209—208
3,065,640	11/1962	Langmuir	73—517
3,133,876	5/1964	Klass	209—1
3,206,987	9/1965	Cunningham	73—517

FOREIGN PATENTS

816,974	7/1959	Great Britain.
---------	--------	----------------

OTHER REFERENCES

American Journal of Physics, vol. 33, No. 5, May 1965, pp. 406, 407; "Electrostatic Separation," by Lewis Epstein. International Science and Technology, July 1966, "Magnetic Fluids," pp. 48—54 and 56, R. E. Rosensweig.

FRANK W. LUTTER, Primary Examiner

U.S. Cl. X.R.

209—208, 172.5; 210—65