United States Patent

Lang

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[54] **ELECTRODYNAMIC PARTICLE SEPARATOR**

[72] Inventor: **James I. Lang,** Oneida, Wis.

[73] Assignee: **John F. Sylvester,** Green Bay, Wis.

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[52] **U.S. Cl.** **209/212,** 209/219, 209/232, 210/222, 55/100

[51] **Int. Cl.** **B03c 1/12,** B01d 35/06

[58] **Field of Search**.....209/219, 232, 220, 222, 214, 209/215, 39 YO, 223, 227; 210/222, 223; 73/61 R, 54; 204/309; 55/100

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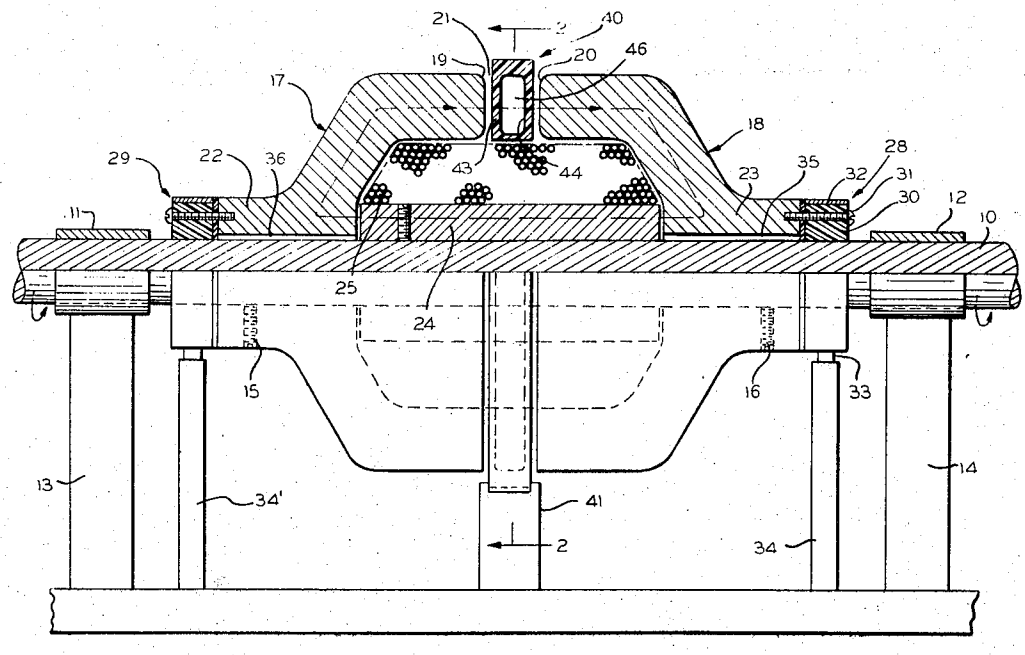
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Primary Examiner—Frank W. Lutter
Assistant Examiner—Robert Halper
Attorney—Wiviott & Hohenfeldt

[57] **ABSTRACT**

Charged particles such as ions in solution or suspended solids having a natural or induced electric charge are separated from or concentrated in the fluid medium in which they are contained. The fluid medium is conducted through a non-magnetic duct through which an intense magnetic flux rotating at high velocity is directed. Particles having opposite polarity charges are deflected in opposite directions and concentrated under the influence of Lorentz forces which are defined as $\vec{F} = q\ \vec{V} \times \vec{B}$, where $\vec{F}$ is the deflecting force vector, q is the magnitude of the charge on a particle, $\vec{V}$ is the velocity vector of the particle and $\vec{B}$ is the magnetic flux vector. A multiported analyzer near the duct exit divides the streams which contain the concentrates from the dilute stream. Means are provided for regulating the flow volume through the ports.

20 Claims, 7 Drawing Figures



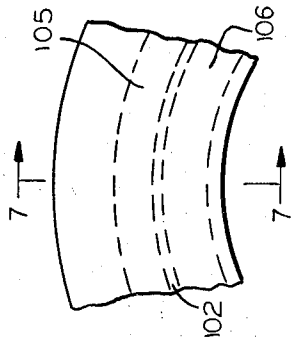


FIG.6

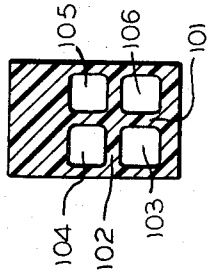


FIG.7

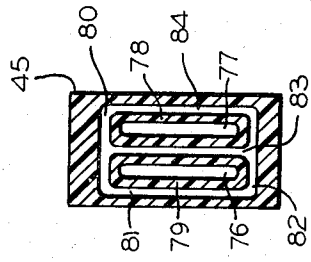


FIG.5

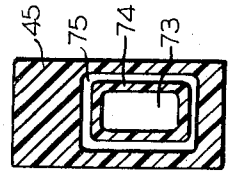


FIG.4

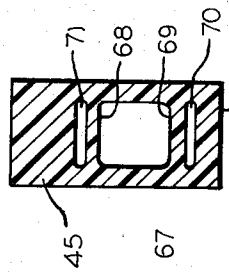


FIG.3

FIG.2

INVENTOR
JAMES I. LANG
BY Wyrott & Hohenfeldt
ATTORNEY

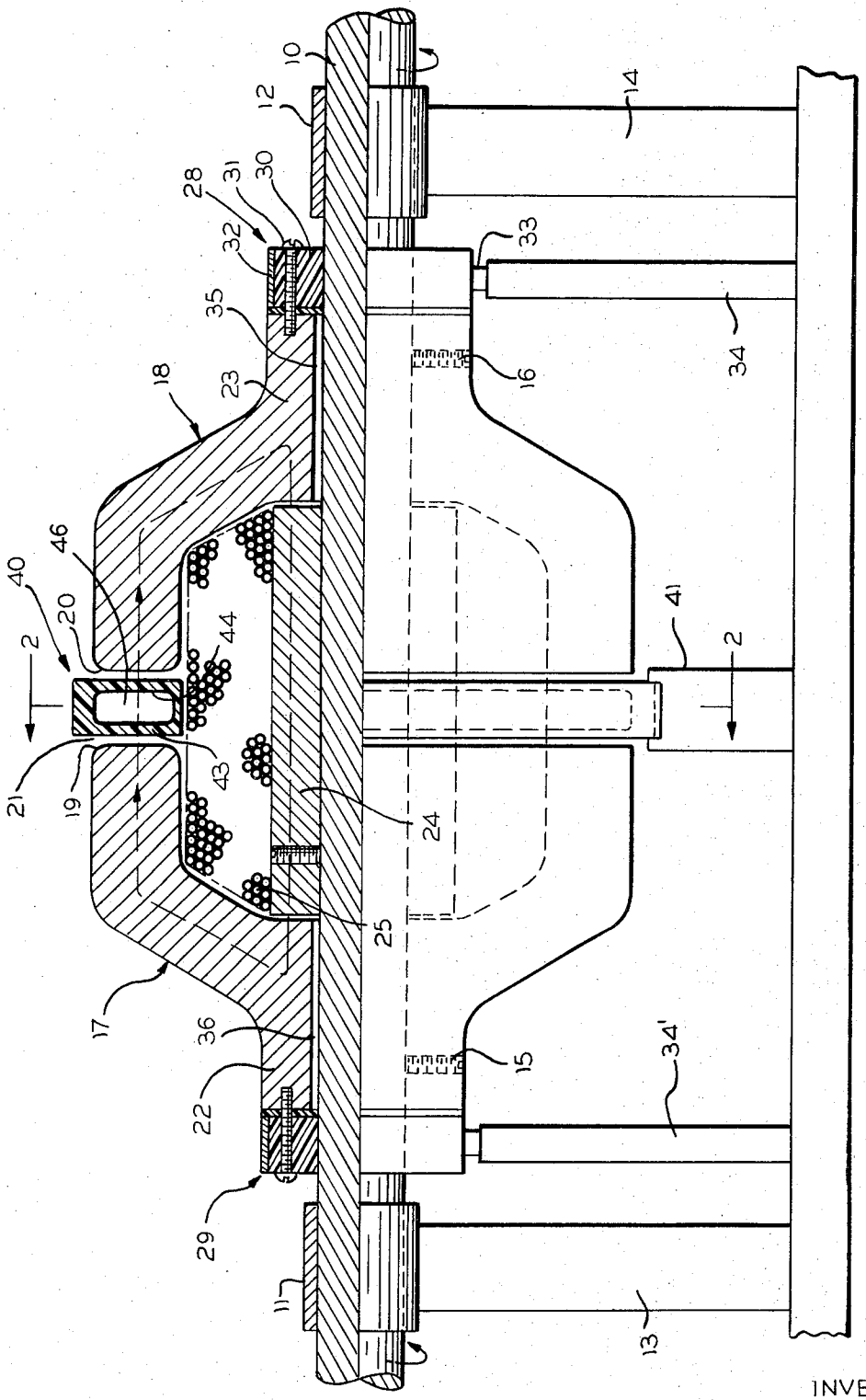


FIG. 1

INVENTOR
JAMES I. LANG
BY Wiviott & Hohenfeldt
ATTORNEY

ELECTRODYNAMIC PARTICLE SEPARATOR

BACKGROUND OF THE INVENTION

Many industries today are faced with the problem of separating fine suspended solids and dissolved ions from fluids. Sometimes it is desired to concentrate or separate fine particles because they or the fluid in which they are suspended have intrinsic economic value. In other cases separation is desired because a fraction of the fluid is intended for disposition as a waste which would be considered a pollutant if discharged into a stream, a lake or the atmosphere. There have been several prior methods of separating fine particles from fluids but none is universally applicable. For instance, electrostatic precipitators remove solid particles having a certain size range from a gaseous suspension but they are not effective for removing particles from a liquid. Various kinds of mechanical filters have also been devised but these usually have limited capacity and require frequent cleaning or replacement of the filter elements. They also impose a severe restriction on the flow rate of the fluid medium passing through them in which case their use may adversely affect the industrial process to which they pertain. Various types of magnetic separators have also been devised, but their use is limited to particles which are magnetically susceptible.

Another process that is used for separating particles is electrophoresis which involves immersing a pair of oppositely polarized electrodes in a fluid which entrains particles whose separation is desired. Negatively charged particles are thus attracted to the anode and positively charged particles to the cathode so that separation or, at least, concentration of the suspended material occurs near the electrodes. Electrophoresis apparatus, however, is subject to electrochemical effects such as the production of gases around one or both of the electrodes, thus changing the potential gradient and the effectiveness of the apparatus.

It should be apparent upon consideration of the aforementioned commercially available devices that there is a critical need for a method and device that will separate or concentrate ions, complexes, organic particles such as proteins, inorganic particles and colloidal substances from a fluid suspension. A typical and heretofore unfulfilled application of such a device is to separate whey and other undissolved organic particles from the fluid wastes which are incidental to the production of cheese. Whey has commercial value but it is often discharged as waste and constitutes a principal source of pollution because its separation has been difficult. Whey is a proteinous substance which has an intrinsic electric charge so that it can be effectively removed, like many other substances, from a liquid suspension by the new electrodynamic particle separator which will be described below.

SUMMARY OF THE INVENTION

According to the present invention, a fluid medium containing ions and suspended solids, hereinafter called charged particles for brevity, is conducted through a curved non-magnetic duct. Adjacent opposed sides of the curved duct are rotating magnets which create magnetic flux lines that are transverse to the flow path of the fluid in the duct. Relative motion is obtained between the charged particles in the suspension and the magnetic field by rotating the magnets at high velocity. The electrostatic charge on the particles reacts with the magnetic field in such manner that particles which are charged with one polarity are deflected radially inwardly and particles which are charged oppositely are deflected radially outwardly so as to create a concentration of these charged particles on the inner and outer interior peripheries of the duct. If all particles have the same charge they will, of course, deflect or migrate in one direction only. The physical laws relied upon to effect particle separation are expressed by the Lorentz equation $\vec{F} = q\vec{E} + q\vec{V}\times\vec{B}$ as will be discussed more fully hereinafter. Fluid flow through the duct is preferably laminar since turbulent flow produces undesirable mixing. The particles are constantly urged in one direction or another in which case they migrate toward opposite walls where they become concentrated in separate streams by the time they are near the exit. The exit end of the duct is provided with a transverse multiple port means to separate the concentrate streams which follow the interior and exterior peripheries of the duct from the more dilute central stream. The duct may be subdivided into several main streams which each have their own means and which are independent of each other. The dilute central stream usually flows from a central port of the port means. The device is adapted to conduct the concentrate and the dilute portions of the fluid along separate paths.

Charged particles having sizes on the order of .01 to 100 microns may be separated or concentrated with the new device. Even magnetically susceptible particles can be separated by the new electrodynamic technique provided the particles are large enough, such as about 10 microns, to accept sufficient charge. In such case, the electrodynamic reaction with the rotating magnetic flux will overwhelm the forces of simple magnetic attraction which predominates in prior art magnetic particle separators. Moreover, the relative velocity between the particle suspension and the rotating magnetic field in prior magnetic separators is, perhaps, up to about 10 feet per second, whereas in the new electrodynamic separator relative linear velocity between the flowing charged particles and the magnetic field is in the realm of 100 to 1000 feet per second or even greater. Thus, field rotation rates ranging from about 1000 to 100,000 revolutions per minute are contemplated in conjunction with fluid suspensions that flow in the same direction or counter to the magnetic field rotational direction. Magnetic flux densities are on the order of 1000 to 25,000 gausses.

A general object of this invention is to provide a new method and apparatus for separating charged particles from a fluid medium by electrodynamic means.

A further object is to provide a separator for fluid suspended particles that are in a natural or induced charged state, that are not necessarily magnetic and that fall within a wide range of particle sizes.

Another object of this invention is to provide a separator for charged particles which effects relative velocity between a magnetic field and the particles not by accelerating the particles to high speed but by revolving magnetic flux at high speed.

More specific objects are to relate magnetic rotation, fluid flow rate, and outlet analyzer geometry in an elec-

trodynamic separator in such manner that optimum concentration or separation of particles results.

More general objects of the invention are to provide a separator which has a relatively simple construction, is rugged and adapted to industrial use, requires little skill to operate, and that performs effectively and is economical to operate. A corollary to these objects is to provide a device which is essentially self-cleaning and requires little maintenance.

How the foregoing and other more specific objects are achieved will appear from time to time throughout the course of the ensuing description of a preferred embodiment of the invention taken in conjunction with the drawings.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is an elevation view, partly in vertical section, of an embodiment of the new particle separator;

FIG. 2 is a transverse cross section, with parts omitted, taken along a plane corresponding with 2—2 in FIG. 1;

FIG. 3 is a particle stream exit port means shown in a cross section taken on a line corresponding with 3—3 in FIG. 2;

FIGS. 4 and 5 are alternative forms of particle stream exit analyzers;

FIG. 6 is a side view of a fragment of a modified duct for use in a particle separator; and,

FIG. 7 is a cross section taken on a plane corresponding with 7—7 in FIG. 6.

DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

Refer to FIG. 1. The new particle separator comprises a shaft 10 which is supported in spaced-apart journals 11 and 12 which are each on suitable mounts 13 and 14. Shaft 10 may be caused to rotate at high speed by any suitable prime mover. Shaft rotational speeds up to 100,000 rpm may be used in some cases with speeds of 20,000 to 30,000 rpm being most usual. This may be accomplished by conventional means such as a steam or air turbine or a relatively low speed electric motor and a step-up gear train, not shown. Another method of obtaining high shaft rotational speeds is to drive the shaft with a directly coupled two-pole induction motor which is energized from a voltage source at a frequency which is some multiple of the normal 60 Hz power line frequency.

Mounted on shaft 10 and fastened thereto with key means such as set screws 15 and 16 are a pair of cup-shaped pole pieces 17 and 18. These pole pieces may be made of soft iron or other ferromagnetic material which has high magnetic permeability. They may also be strong permanent magnets. The respective pole pieces terminate in flat annular pole faces 19 and 20 which define an air gap 21 between them.

Fixed to shaft 10 in the space created between hubs 22 and 23 of the pole pieces is a cylindrical core 24 which also preferably has high magnetic permeability. The annular space surrounding core 24 is occupied by many turns of insulated wire constituting an electromagnet coil 25. Coil 25 is suitably insulated from core 24 and restrained by suitable banding, not shown, to prevent centrifugal destruction of the coil when it is rotated at high speed. Fastened to the axial ends of the magnet hubs 22 and 23 are two similar slip ring assemblies 28 and 29. These slip rings are conventional in that they comprise an insulating cylindrical disk 30 which is centrally bored to fit over shaft 10 as exemplified by assembly 28. The insulating disk is fastened to the axial end of magnet hub 22 by means of circumferentially spaced apart screws 31. Pressed or molded on the outer periphery of insulating disk 30 is a metal slip ring 32. Slip ring 32 rotates and makes sliding contact against a graphite brush 33 which is supported in an insulating brush holder 34. The brush holder has the usual internal springs, not shown, for urging the brush against slip ring 32. The bores of the hubs 22 and 23 may be slotted axially as at 35 and 36 respectively, to provide passages for lead wires that connect the opposite ends of coil 25 to the slip rings. A conductor, not shown, runs through the interior of each brush holder 34, 34' and connects with a source of d-c power, not shown. Generally, magnetic flux density will be on the order of 1000 to 25,000 gausses whether the flux is produced with permanent magnets or electromagnets.

Interposed between pole faces 19 and 20 in air gap 21 is a curved duct 40 of non-conducting and non-magnetic material such as plastic. The duct has a rectangular cross section with rounded corners as shown in FIG. 1 but it may be round or otherwise shaped cross sectionally provided the magnetic pole pieces are suitably shaped. The center channel 46 of the curved duct 40 is substantially coincident with the axis of shaft 10 and surrounds it. The duct is supported on a pedestal 41 which is merely symbolized and may take many forms. From the description thus far, it should be evident that when coil 25 is energized from a d-c source, cup-shaped pole pieces 17 and 18 will be magnetized and will serve as part of a magnetic circuit which is interrupted annularly by air gap 21. In other words, the magnetic lines of force will extend across gap 21 between pole faces 19 and 20 and in so doing will traverse duct 40 axially to produce a substantially uniform distribution of magnetic flux through the duct. Accordingly, when shaft 10 and pole pieces 17 and 18 are rotated at high speed, the flux lines bridging gap 21 and the duct will be cut by any charged particles that are standing or are in motion within duct 40. The rate at which the flux lines are cut by any selected particle depends on the rotational velocity of the pole pieces and the flow direction and velocity of the fluid within the duct. As a general rule, high relative velocity between the magnetic field and particles will produce a greater electrodynamic interaction between the flux and the particles but as will appear later, optimum particle separation efficiency may occur within a comparatively narrow relative fluid velocity range.

Generally, magnetic flux moving at a linear velocity in the range of 100 to 1000 feet per second is contemplated. The most likely maximum linear velocity limit would be the speed of sound in air. Exceeding the speed of sound would require extremely high magnet rotational speeds and would give rise to difficult engineering and design problems as is well known.

A vertical section taken through duct 40 in a plane which is normal to the shaft axis is shown in FIG. 2. The axis of shaft 10 coincides with the center of the full circle 42 which defines the radially interior wall of the duct. The axial or sidewalls of the duct are marked 43

and 44, the latter appearing only in FIG. 1. The radially displaced outer wall of the duct is marked 45 and the annular duct channel is marked 46. It should be observed that channel 46 is substantially a complete circle or nearly 360° in angular measurement about the axis of shaft 10, so the magnetic flux acts on the fluid suspended particles for the maximum amount of distance and time.

FIG. 2 shows that the duct has a radial extension 47 whose width is substantially the same as that of the duct in this example. Extension 47 has a lengthwise partition wall 48 which divides the extension into a fluid inlet channel 49 and multiple fluid outlet channels comprising an inside annular channel 50, a central channel 51 and an outside channel 52. Fluid may exit from the duct and the last named three channels through holes 53, 54, and 55. Fluid enters the duct through an inlet 56 and follows a path through inlet channel 49 whereupon it may enter and circulate around main duct channel 46. There is preferably a diverter 57 located in duct channel 46 to minimize stagnation but not to cause turbulence since it is desirable that the fluid suspension flowing through duct channel 46 be laminar rather than turbulent.

For reasons which will be explained later, it is desirable to regulate the quantities flowing in the outer annular concentrate stream 52 and the inner annular concentrate stream 50 as compared with the quantity flowing in the more dilute central stream 51 and to coordinate these quantities with fluid velocity and the area of the exit ports. To provide this function, a throttle valve 58 is used to control jointly the effluent from channel 50 and its outlet 53 and channel 52 and its outlet 55. Thus, valve 58 has its input side connected with outlets 53 and 55 by means of pipes 59 and 60 which are merely symbolized as straight lines. There is also a valve 61 which is connected with central stream outlet 54 by means of a pipe 62 which is symbolized by a straight line.

In accordance with known physical laws, when a fluid suspension of charged particles is conducted through duct 46 as, for example, in the direction of the arrow 63 while magnets 17 and 18 are rotating with shaft 10, the charged particles will cut the flux lines relatively between pole faces 19 and 20 and there will be an electrodynamic interaction between the magnetic flux and the particles. The particles may be treated as having a velocity vector and the flux lines may be treated as a vector quantity. The force produced on the particles will thus be a vector quantity whose direction will be perpendicular to the plane defined by the velocity and flux vectors. The magnitude of the force is proportional to the sine of the angle between the velocity vector and the flux. Suspended particles which are charged with one polarity will, therefore, be deflected toward inner wall 42 of the duct, and particles having the opposite polarity charge will be deflected toward the outer wall 45 in this embodiment. These particles are acted upon by the magnetic field substantially during the particles' entire transit time in duct channel 46 in which case the oppositely charged particles will migrate or be deflected toward the opposite walls of the duct and by the time the particles arrive in the exit region 64 of the duct they will be highly concentrated along the radially separated insides of the duct walls. On the other hand, the central stream of the suspension will have had charged particles removed and will be more dilute than when the fluid suspension was admitted to the interior of duct 46. The two concentrate streams may be discharged separately or jointly as through valve 58 and its associated piping as explained earlier. The central diluted stream may be discharged through valve 61 as previously explained.

The physical law governing particle separation in accordance with the invention and as outlined in the preceding paragraph is expressed by the Lorentz equation:

$$\vec{F}=q\vec{E}+q\vec{V}\times\vec{B}$$

where $\vec{F}$ is the force on the charged particles, the force being a vector quantity, q is the electric charge on a particle, $\vec{V}$ is a vector quantity representing the relative velocity of the particle with respect to the magnetic flux, $\vec{B}$ is the magnetic flux vector. The magnitude of the $\vec{V}\times\vec{B}$ vector is given by $VB\sin\theta$, where θ is the angle between vectors $\vec{V}$ and $\vec{B}$. Any consistent set of units may be used in connection with the above general form of the Lorentz equation but the MKS system of units is usually implied as is the case herein. In the absence of an electric field, as in the preferred embodiment of the present invention, the $q\vec{E}$ term may be disregarded.

In accordance with the Lorentz equation, a charged particle which is in a relatively moving magnetic field will be deflected at a right angle to both the velocity vector $\vec{V}$ and the field vector $\vec{B}$. As θ, the angle between the velocity vector and the flux vector, approaches zero, the sine of θ approaches zero and the component of the velocity which is normal to the flux lines approaches zero. Hence, the deflecting force approaches zero. When θ approaches 90°, the sine of θ approaches one and the component of velocity which is normal to the flux lines is maximum in which case the deflecting force $\vec{F}$ is maximum.

The trajectory of the individual charged particles in the fluid is more complex than would be the case if the magnetic field and charged particles were interacting in a vacuum. The trajectory of a particle from any given position in stream toward a duct wall is affected by intermolecular forces of an electric nature which originate from the fluid medium. In addition, the relative velocity vector of a particle with respect to the magnetic flux lines may be affected by a velocity vector which is additive or subtractive depending on whether the fluid is flowing in the direction of rotation of the magnetic field or counter to it. The dynamics of viscous flow dictate that fluid velocity will be maximum at the center of the duct and reduced to substantially zero at the walls of the duct in which case the fluid velocity component of the trajectory will be affected correspondingly. The result of these various effects is for the particles to drift or migrate toward the duct walls rather than to follow the trajectory that they would follow if the particles were in free space and influenced solely by Lorentz forces. In any case, however, where the circumferential length of the duct is adequate there will be a concentration of oppositely charged particles at the respectively radially inward and radially outward walls of the duct and these particles will be swept along by the fluid flow toward the exit region of the duct where they will be at maximum concentration.

There are some additional phenomena to which attention must be given. For instance, when particles with opposite charges begin to concentrate on the opposite walls of the duct, a more sparse population of charged particles exists in the central stream. The collective force of the concentrated charges tends to repel particles with like charges that remain in the central stream. These forces must be subtracted from the force which puts the particles in a trajectory that concentrates them. Fluid flow also has an effect on the direction and rate at which the particles will drift or migrate to the duct walls. Fluid flow causes a radial pressure gradient which results in a secondary flow of charged particles. Secondary flow of particles is usually in two closed loops which have the same direction in the center of the duct as they flow toward the outer duct periphery and an opposite common direction along the radially spaced but long duct wall faces. This secondary flow rearranges the particles which have a charge of one polarity by dragging them along the center of the duct in a radial direction while charges of an opposite polarity are dragged along opposite radial walls in the opposite direction. Thus, at least, for certain kinds of charged particles there may be a high concentration of charges in the central annular region as well as on the two peripheral annular regions. More information on the nature of secondary flow resulting from a fluid flowing around a curve is obtainable in the book Rouse, H. & Howe, J. W., *Basic Mechanics of Fluids*, John Wiley & Sons, Inc. 1953, p. 157, Library of Congress Catalog Card No. 53-6518.

Some charged particles, particularly colloids, have exhibited a propensity to collect almost exclusively on the internal peripheral walls and on the radially spaced sidewalls with a central diluted region being framed or surrounded by a complete rectangle of concentrates. Tests made on dilute solutions or dispersions showed that the particles were concentrated almost exclusively on the internal surfaces of the radially spaced duct walls.

The foregoing discussion provides a basis for going ahead with a description of the multi-ported means which is interposed inside of the duct in the vicinity of exit region **64**. The port means used in the FIG. **1** and **2** embodiment comprises a large central opening **67** which is rectangular in cross section as can be seen in the cross sectional view of FIG. **3**. This rectangular port **67** is defined by spaced apart end walls **68** and **69**. The end walls also serve as one side of narrow concentrate ports **70** and **71** through which the concentrates exit from duct **46**. This is a configuration which has been successfully used in connection with separating proteinous particles from a liquid suspension.

An alternative form of exit port means which is useful for concentrating certain types of particles is shown in FIG. **4** oriented as it would be if it were viewed toward the line **3—3** in FIG. **2**. In the FIG. **4** embodiment, there is a rectangular central port **73** through which the solution which has been deprived of most of its charged particles flows. This central port is bounded by a continuous rectangular wall **74** which also defines a rectangular annulus **75** through which the concentrated charged particles exit. This exit port means configuration is one of the options a user may request for treating a particular suspension which is most efficiently analyzed with this type. For instance, this type of port means may be most effective for treating colloidal suspensions.

An alternative form of port means is depicted in cross section in FIG. **5**. This port means has two central ports **76** and **77** which are defined by rectangular tubular partitions **78** and **79**. There are also several annular regions **80–84** through which the concentrates exit. Concentrations of charged particles accumulate in the annular regions **80–84**. This design is particularly effective in removing the charged particles which tend to follow the central annulus **83** due to secondary flow which results from polarization as discussed above. In reality, the presence of the median annular duct **83** has the effect of reducing polarization since charged particles of one polarity will tend to flow in a single direction along region **83**. This charge and concentrate distribution pattern, of course, actually occurs along the main circular duct channel **46** and the port means configuration is merely that which will most effectively discharge the concentrates without remixing them with the more dilute solution. The multi-ported means shown in FIG. **5** has exhibited high efficiency in removal of whey from the liquid milk residue which is a by-product of the cheesemaking process.

It should be understood that the duct need not be rectangular in cross section. Particle separation can be obtained in ducts that have a circular or an elliptical cross section and other configurations too. A rectangular cross section with slightly rounded corners appears to have very good separating properties. Various cross sectional shapes can be made having an area for the dilute part of the stream and isolated annular areas for the concentrates.

The internal dimensions of the main duct channel influence charged particle separation efficiency. The greater the radial dimension or height L of the duct in comparison with the axial dimension or width W of the duct, the larger will be the storage area for charges swept to the sides of the duct by secondary flow. If W is relatively small, the air gap between the magnetic pole faces may be small in which case the reluctance of the flux path is reduced and the flux B will be advantageously more intense. Findings thus far indicate that if the ratio of L to W is very much greater than 5:1 flow instability results and the separation process is defeated. If the ratio of L to W is less than 1:1, the air gap is too large, field intensity across the duct suffers and the charge storage area is too small for good separation. It has been determined, however, that polarization and secondary flow become unstable at large ratios of L:W such as 10:1. The preferred ratio range of L:W appears to be 1.5:1 to 5:1 although it has not been confirmed that these are the absolute limits for all fluids and all types of charged particles.

Anyone desiring to design a particle separator such as is described above might assume that at very low fluid flow rates through duct channel **46** maximum separation of particles would occur because of there being maximum residence time of the particles in the magnetic field. This is not always true. At low flow rates comparatively low separation occurs because the magnitude of secondary flow is dependent upon the square of the average velocity of the particles through the duct, and, with negligible secondary flow, polarization quickly occurs, stopping further separation. On the

other hand, at excessively high flow rates, the residence time of the charged particles in the magnetic field is too short for good separation. It is not easy to specify an intermediate fluid flow rate which will optimize particle separation because this will depend on a number of selectable design parameters such as the radius of curvature of the duct median line and the cross sectional dimensions of the duct.

When fluid flows in a laminar condition within an enclosed duct, a velocity gradient across the flow path is typically parabolic which means that the flow near a wall is slowed by friction between the wall and the fluid. Superimposed on the velocity gradient in this device is the secondary flow, which makes the velocity gradient steeper than that existing in straight channels. It is, of course, desirable that the linear fluid velocities at both dilute solution exit ports such as **76** and **77** in FIG. **5** be equal to the velocity of the annular exit ports for the concentrates such as ports **80–84** in this figure. To obtain this equality, throttle valves **58** and **61** are provided. These valves can be adjusted to balance the flow as required. It has been found that optimum separation occurs when the ratio of the area of the dilute exit port to the area of the annular concentrate exit ports is in a range of about 1.5:1 to 5:1.

It should be apparent that flow of the fluid medium through the duct should be laminar rather than turbulent if charged particle separation or concentration is to be successful. Those who are knowledgeable in fluid mechanics will appreciate that whether flow is laminar or turbulent depends on the Reynolds number R_e and the Dean number D of the system. Generally, if the Reynolds number is 2000 or less, flow will be laminar in straight flow but with radial geometry laminar flow may exist at Reynolds numbers which are 3.5 or more times as high. As is known, when the Reynolds number, which is dimensionless, is determined for a particular design it can be used as a criteria for maintaining laminar flow in designs that are scaled up or down as long as fluids of the same viscosity are involved and the dimensions and flow rates are proportional.

The general expression for the Reynolds number is:

$$R_e=(4R_HV\rho)/\mu$$

where V is the fluid characteristic velocity, R_H is the hydraulic radius of the duct defined as its cross sectional area directed by the wetted periphery, ρ(rho) the density of the fluid and μ(mu) the viscosity of the fluid. This is an expression of the ratio of inertial shear forces to viscous shear forces in a flow system and predicts that if the Reynolds number is high, inertial forces will dominate, provided viscosity is low, and if low, viscosity will dominate. For pipe flow, $4R_H$ is equal to the pipe diameter, but for a rectangular duct, as is the case here,

$$R_H=LW/2(L+W)$$

where L is duct length, and W is duct width.

The Dean number D is another similarity parameter that is useful for predicting onset of turbulent flow when curvature of the flow path is important. The general expression is:

$$D=\frac{1}{2}(R_e)\left[\left(\frac{2R_H}{r}\right)\right]^{1/2}$$

where R_e is the Reynolds number, R_H is hydraulic radius of the duct and r the radius of curvature of the duct center line. Thus, onset of turbulent flow in a curved duct depends on the Reynolds number R_e and the ratio of $2R_H/r$. With the geometry described heretofore, Reynolds numbers as great as 7500 and Dean numbers as great as 1000 are expected with ratios of $2R_H/r$ of about 1:14. In summary, optimum flow without turbulence is a function of (R_e, L/W, D, $\vec{V}\times\vec{B}$).

Thus, the design sequence is to select a magnet core mean radius and cross section. The radius of the duct r will have to correspond with the radius of the core and the radial length of the core will have to be the same as L of the duct. Since the ratio of L:W is preferably about 5:1 the width W of the duct can be established. Now the Dean number has a ratio of $2R_H:r$ in which case the above design sequence dictates a ratio of about 1:14. This ratio would remain the same regardless of the dimensions and capacity. The critical Reynolds number above which turbulence might occur depends on $2R_H:r$. At 1:14 the critical Reynolds number is about 7500. Since laminar operation is required, a maximum Dean number of about 1000 is expected. Models tested have had best separation of particles at lower Dean numbers, as low as 80, but tests show that if the product of fluid velocity V and flux B are made larger, best separation will occur at Dean numbers much greater than 80 up to about 1000.

The embodiment of the invention shown in FIG. **1** has the faces **19** and **20** of the cup-shaped magnetic pole pieces **17** and **18** on opposite axially separated sides **43** and **44** of the main duct **40**. The magnetic lines of force thus extend across the air gap **21** and through duct **40** in an axial direction. This results from the diameters of the pole pieces **17** and **18** being equal in which case it is most convenient to interpose the duct between the pole faces. It should be understood, however, that other arrangements of the pole pieces may be used to create an air gap across which the magnetic flux is projected and in which a non-magnetic duct may be located. For instance, the diameter of one pole piece such as **17** may be made considerably smaller than the internal diameter of the other **18** in which case the former may be fit axially within the other and the annular air gap so created may be occupied by a circular duct as in the present case. The different direction of magnetic flux with respect to the direction of magnet rotation would, of course, result in the charged particles being deflected primarily in opposite axial directions rather than radially as in the above-described embodiment.

Permanent magnets can also be used for generating a rotating magnetic field in which case one may take the form of a shaft mounted disk that is inside of the circular duct opening and the other may be essentially a ring which is also on the shaft but outside of the circular duct. The pole pieces may also be fabricated from individual magnet segments with non-magnetic circumferentially spaced gaps between them if desired. The electromagnetic poles may also be made as spoked wheels with a segmented rim. The magnet coils may be wound on the spokes of magnetically permeable material. The magnetic field may, in any case, be caused to rotate in a horizontal plane about a vertical axis and the duct may be horizontally oriented instead of vertically as shown herein.

The separator can also be constructed so that the charged particles are not carried through nearly a whole circle duct as in the described embodiment but only through a semi-circle. Sometimes maximum separation is achieved when the particles have traversed a semi-circle as when the mass of the particles, their charge strength, duct curvature, duct cross section and the strength and velocity of the rotating magnetic field have an optimized relationship. It is then possible to split the duct into two substantially semi-circular adjacent duct sections which each have an inlet at one end and an exit analyzer at the opposite end, the inlet of one duct section being diametrically opposite from the inlet of the other section and the same being true of the exit ports. The ducts may also be nearly full circles and arranged adjacent each other or concentrically, the object being of course, to reduce the critical Reynolds number R_e by reducing the hydraulic radius R_H.

In large capacity particle separators a greater total volume of fluid is passed through the duct but it is still desirable to maintain the low Reynolds numbers of smaller machines in order to assure laminar rather than turbulent flow. Thus, in large separators the duct can be subdivided cross sectionally to create two or more parallel paths which are coextensive in length and really constitute individual curved adjacent ducts in a common magnetic field. Each of the duct subdivisions will have its own multiple port means as in the cases described above where only one duct was employed.

FIG. **6** shows a fragment of a curved alternative form of duct which is subdivided or partitioned longitudinally and FIG. **7** shows a cross section of it. Thus, there are radial and transverse partition walls **101** and **102** respectively, defining in this case four parallel curved ducts **103–106**. It will be understood that each duct will have its own inlet, analogous to **56** in FIG. **1**, and its own multiport means analogous to those shown in FIGS. **3–5** or they may have other forms. This multichannel duct will be interposed between rotating magnets as is the case with the single duct in FIG. **1**.

As mentioned heretofore, some suspended fine particles are not inherently charged and must have a charge induced. This is accomplished easily by running the fluid suspension through a pipe made of insulating material in which there are at least a pair of transverse metal screens spaced from each other by about an inch. Each screen is connected to an opposite polarity terminal of a d-c source which will have low voltage in any case and should be about 1.5 volts for water suspensions. As the fluid suspension flows through the screens its particles adopt a charge after which the suspension is fed to the particle separator duct inlet.

In summary, the new electrodynamic particle separator is characterized by having a rotating magnet act on a rotating stream of charged fluid entrained particles at optimum relative rotational speeds. The particles are conducted through a duct which terminates in a transverse multiported means that separates the concentrates and dilute streams in conformity with the manner in which these streams are generated in the duct. Although an embodiment of the invention has been described in considerable detail, such description is to be construed as illustrative rather than limiting, for the new process and apparatus for separating particles may be variously embodied and is to be limited only by interpretation of the claims which follow.

I claim:

1. A Lorentz-force method of concentrating fluid suspended charged particles in a stream that is separable from the more dilute fluid stream, said method comprising:

a. admitting said charged particle containing fluid into a curved substantially nonconducting and nonmagnetic duct so that the fluid flows around the interior of the duct in a direction that is substantially normal to a cross sectional plane of the duct,

b. disposing magnetic pole pieces having opposite polarity on opposite sides of the duct to produce a magnetic flux which is substantially uniform about the fluid flow path during rotation and has a vector substantially normal in direction to the flow direction of the fluid,

c. rotating said magnetic pole pieces along a curved path defined by the duct at a velocity which is high compared to the fluid velocity and which has a velocity vector substantially normal to said flux vector to thereby produce an intense Lorentz force to cause the charged particles to migrate substantially normal to the plane defined by the velocity vector of the flux and flux vector thereby causing the fluid stream to separate into concentrate and dilute portions, and

d. passing said portions through ported separating means interposed transverse to the fluid flow direction in a curved part of the duct whereby to permit exiting the dilute and concentrate portions from the duct in substantially separate paths.

2. The method set forth in claim **1** wherein:

a. said magnetic flux is rotated at a rate in the range of about 1000 to about 100,000 revolutions per minute.

3. The method set forth in claim **1** wherein:

a. the magnetic field is moved at a linear velocity in the range of 100 to 1000 feet per second.

4. The method set forth in claim **1** wherein:

a. the flux density of the magnetic field is in the range of 1000 to 25,000 gausses.

5. Apparatus for concentrating charged particles in a fluid suspension with Lorentz forces and for separating the concentrates from the more dilute part of the suspension comprising:

a. a curved duct means of nonconducting and nonmagnetic material, said duct means having a fluid inlet and an exit region angularly displaced within the duct means from said inlet,

b. magnetic pole means of opposite polarity on opposed sides of the duct means for producing a substantially uniform magnetic flux along the fluid flow path during rotation which has a vector that is directed substantially normal to the fluid flow direction within the duct means,

c. means for rotating said pole means jointly about the duct at high angular velocity whereby the flux has a velocity vector substantially normal to said vector to produce an intense Lorentz force on the charged particles causing them to migrate substantially normal to the plane of the flux vector and the velocity vector of the flux in the duct means to form concentrate and dilute streams,

d. multiport means disposed transversely to the fluid flow path in a curved part of the duct means and near the exit region thereof, at least one of the ports being positioned to pass a concentrate stream and at least another of said ports being positioned to pass a more dilute stream.

6. The invention set forth in claim **5** wherein:

a. said duct means has a radially extending fluid outlet means located beyond said port means in a direction of fluid flow, said outlet means having isolating channel means for directing the concentrate and dilute streams out of the duct means.

7. The invention set forth in claim **6** including:

a. valve means communicating with said channel means for regulating the flow volume of the concentrate and dilute streams.

8. The invention set forth in claim **5** wherein said port means is characterized by it having:

a. a substantially central dilute stream port, and

b. concentrate stream ports which have dimensions radially of said duct means that are less than the radial dimension of said dilute stream port, said concentrate stream ports being located radially inwardly and outwardly, respectively, from said dilute stream port.

9. The invention set forth in claim **5** wherein said port means is characterized by it having:

a. a radially and axially bounded substantially central dilute stream port, and

b. an annular concentrate stream port surrounding said dilute stream port.

10. The invention set forth in claim **5** wherein said port means is characterized by it having:

a. at least two central dilute stream ports being elongated radially and being axially spaced from each other to define a central radially extending concentrate stream port therebetween, and

b. a continuous narrow concentrate stream port surrounding said dilute stream ports and said radially extending concentrate stream port.

11. The invention set forth in claim **5** including:

a. a shaft on which said pole pieces are positioned in spaced relationship to create a flux gap in which said duct means is positioned.

12. The invention set forth in claim **5** wherein:

a. said pole pieces are concave and are in opposed relationship, the ends of said pole pieces constituting annular pole faces which are axially spaced from each other to define a magnetic flux gap in which said duct means is disposed,

13. The invention set forth in claim **5** including:

a. means subdividing the aforesaid duct means into individual duct means which are substantially coextensive with the aforesaid duct means.

14. The invention set forth in claim **5** wherein:

a. the internal dimension of the duct means in the direction between said pole pieces is defined as L and the dimension of the duct means perpendicular to L is defined as W and the range of ratios between L and W is 1.5:1 to 5:1.

15. The invention set forth in claim **5** wherein:

a. the range of area ratios for said dilute stream port to said concentrate stream port is 1.5:1 to 5:1.

16. The invention set forth in claim **5** wherein:

a. the range of ratios between $2R_H/r$ is between 1 and 14 where R_H is the hydraulic radius of said duct means and r is the mean radius of curvature of said duct means.

17. The invention set forth in claim **5** wherein:

a. said pole piece rotating means rotates the same at a rate in the range of 1000 to 100,000 revolutions per minute.

18. The invention set forth in claim **5** wherein:

a. the linear velocity vector of said flux is in the range of 100 to 1000 feet per second.

19. The invention set forth in claim **5** wherein:

a. said flux is in the range of 1000 to 25,000 gausses.

20. The invention set forth in claim **5** wherein:

a. the said pole means on opposed sides of the duct means each have magnetic material faces adjacent the duct means which faces are substantially continuous in a direction about their rotational axis to thereby produce a magnetic flux which is substantially uniform around the duct means when the pole means are rotated.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,693,792 Dated SEPTEMBER 26, 1972

Inventor(s) JAMES I. LANG

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In claim 12 add the following:

--b) a shaft on which said pole pieces are mounted,

c) electromagnet coil means in the concave space of the pole pieces, and

d) slip rings mounted to rotate with said shaft and connected to opposite ends respectively of said coil means.

Assignment should indicate: --Undivided 1/2 interest to John F. Sylvester.--

Signed and sealed this 3rd day of April 1973.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents