June 20, 1967 J. P. LEROUX 3,326,459

PARTICLE CLASSIFIER

Filed Oct. 7, 1964 3 Sheets-Sheet 1

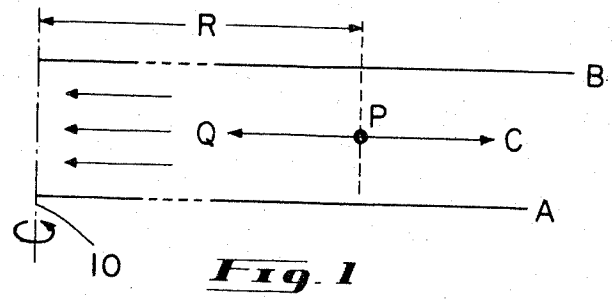


Fig. 1

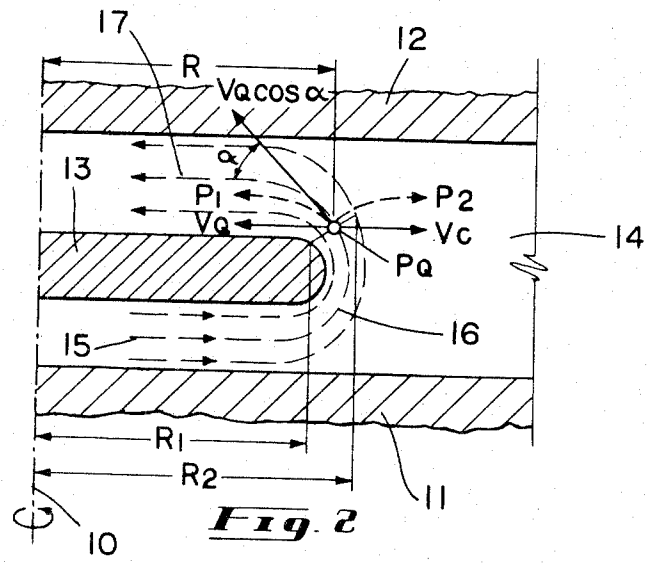


Fig. 2

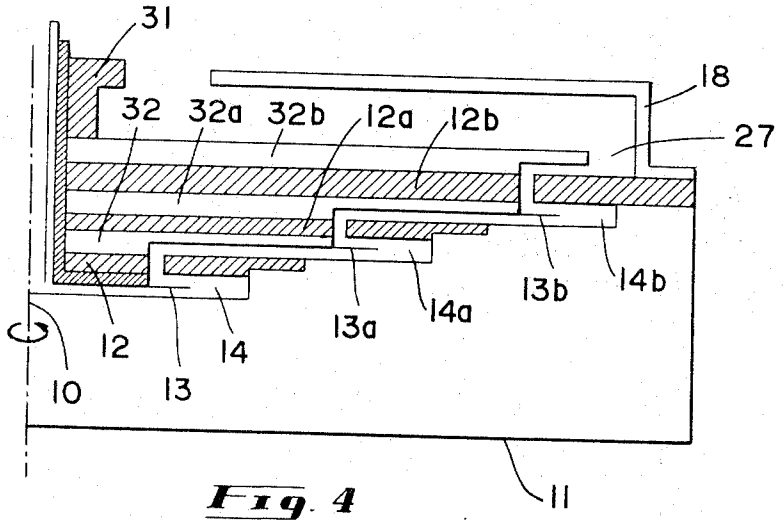


Fig. 4

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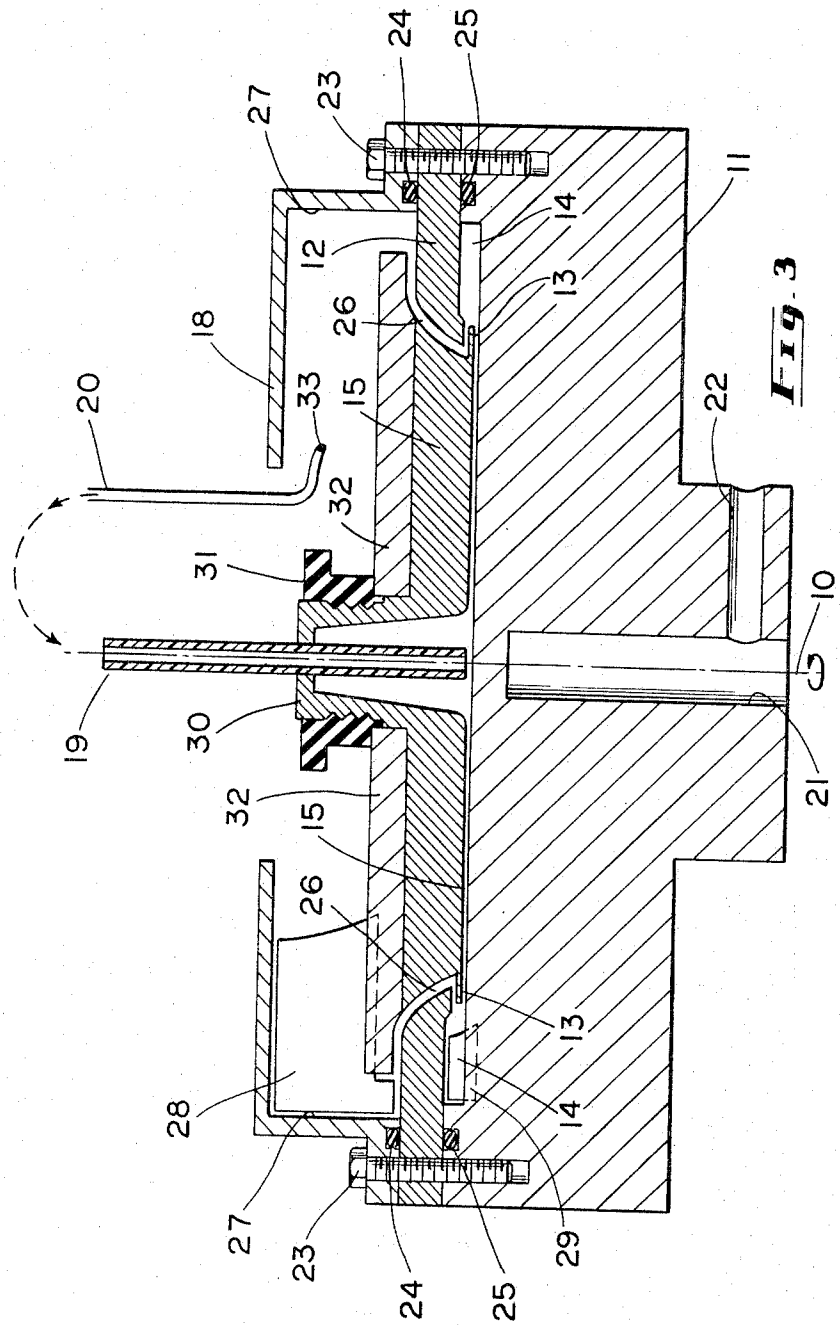


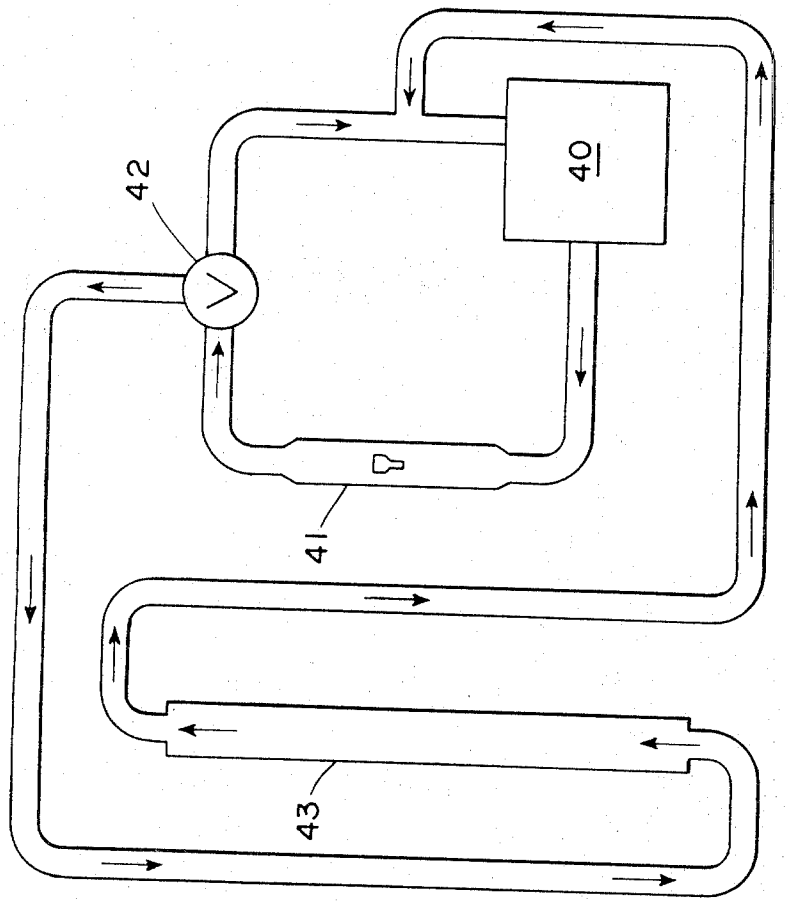
Fig. 3

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Fig. 5



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PARTICLE CLASSIFIER

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5 Claims. (Cl. 233—28)

The present invention relates to a method and apparatus for classifying or separating particles according to their relative size, and in particular to such a method and apparatus employing centrifugal forces and hydrodynamic forces.

The present invention provides a solution to the problem of separating particles which are suspended in a liquid in two or more fractions according to their size. In many instances it is necessary to separate particles accurately and quickly in size ranges from 0.5 micron up to 10 microns, where 1 micron is 10^{-4} cm. Prior to the present invention the separation of such particles into fractions by size in the size range up to 10 microns has been carried out by decantation and gravitational elutriation which requires between 10 and 500 hours to completely separate one gram of particles. Accordingly the great length of time required has been unsatisfactory for separation of such fractions. In addition it has required considerable space, equipment and many gallons of liquid, the temperature of which must be very critically controlled during the process. In accordance with the prior art the fractional decantation time may be considerably reduced by centrifugation, but since the centrifugal force acting on the particles increases with the square of the radius of gyration, the settling velocity is not uniform and considerable time must be given to the calibration of the instrument for each type and definite size of particles.

Accordingly none of the prior art devices can simply and reliably separate particle fractions in the range from one-half to 10 microns.

The present invention provides a simple and reliable particle classification centrifuge which may be used accurately to separate fractions of a particle suspension in a liquid and which operates on principles not heretofor used in such a particle classifier. In accordance with the invention, liquid containing particles to be classified is rotated at a predetermined angular speed, the suspension to be classified flowing outwardly from the axis of rotation and being suddenly diverted for a short distance in a direction parallel to the axis of rotation. The suspension is then caused to flow inwardly toward the axis of rotation whereby those particles whose diameter is larger than a predetermined size will be accelerated radially away from said axis and those particles less than said diameter will be transported toward the axis by the liquid. The apparatus of the invention gives a sharp definition between those particles which are accelerated away from the axis and deposited on the wall of the centrifuge and those which are transported by the liquid toward the axis of rotation. In accordance with a further aspect of the invention more than one stage of separation may be provided in a particle classifier and separated particle fractions may be obtained from the deposit on the walls of the classifier at each successive stage. In accordance with a further feature of the invention means are provided in the centrifuge for collecting the liquid after particle classification and for recirculating the liquid back to the inlet of the centrifuge.

In the operation of a centrifuge in accordance with the present invention, the centrifuge is accelerated to its proper rotational speed, the flow of liquid through it is adjusted to a predetermined value and the suspension is then introduced into the centrifuge and classified therein. It is essential that the suspension not be introduced into the centrifuge until the proper operating conditions are obtained otherwise the classification will not be accurately carried out, since the process of the present invention is dependent upon the rotation rate and the velocity of flow of the liquid through the centrifuge, as is detailed more fully below.

It has been experimentally verified that the drag on a spherical body in a fluid is equal to

$$Q=3\pi\nu V_c d \tag{1}$$

where

V_c=terminal constant velocity of particle,
ν=viscosity of the fluid, and
d=diameter of the particle,

Also, the centrifugal force acting on a spherical body moving circularly with a fluid around an axis is expressed as

$$C=\frac{\pi}{6}d^3R\omega^2(\rho-\rho_o) \tag{2}$$

where

R=radius of gyration of the particle,
ω=angular speed in radians of the system,
ρ=specific gravity of the particle,
ρ_o=specific gravity of the fluid,
d=diameter of the particle.

Equating the two forces Q and C in (1) and (2) one obtains

$$V_c=\frac{R\omega^2(\rho-\rho_o)d^2}{18\nu} \tag{3}$$

where V_c is now the velocity at which the drag and centrifugal forces are equal and opposite. Since in this equation V_c corresponds to the terminal constant velocity of a particle of size d with respect to the fluid, the fluid must move radially towards the center at this velocity at radious R. Designating the height of the total area of flow by H, and remembering that $\omega=2\pi N$ (N=number of revolutions per unit time), the flow through the area

$$H \text{ is } F=2\pi RHV_c\frac{4\pi^3}{9\nu}(\rho-\rho_o)H(RNd)^2 \tag{4}$$

Equations 3 and 4 indicate that a particle of diameter d suspended in a streamline fluid moving radially at constant flow towards the center of rotation between two parallel disks would be in equilibrium, neglecting gravity, at a radius R as long as the angular speed of the system remains constant. By extension it can be stated that a particle having a diameter d_2 greater than d would start moving away from the axis of rotation being accelerated under the resultant force of both the increasing centrifugal force C and the decreasing drag force Q. On the other hand, a particle having a diameter d_1 less than d, would be accelerated towards the axis under the resultant of both the increasing drag force Q and decreasing centrifugal force C.

The theoretical situation just described shows that a very sharp separation should be obtained with some device which would actually approach the conditions imposed by Equations 3 and 4. The present invention provides such a device.

In drawings which illustrate the principles and embodiments of the invention,

FIGURE 1 is a schematic diagram illustrating the principle of separation of the invention in relation to Equations 1 and 2,

FIGURE 2 is a schematic diagram illustrating the principle of operation of separation apparatus according to the present invention,

FIGURE 3 is a cross-section of a preferred form of apparatus in accordance with the invention,

FIGURE 4 is a cross-section of a multi-stage separator, and

FIGURE 5 is a schematic diagram showing the use of apparatus according to the present invention.

FIGURE 1 illustrates schematically the separation principle of apparatus of the present invention. A particle ideally introduced at point P at radius R from the axis of rotation **10**, and positioned between plates A and B is under two influences. The first of these is the flow toward the axis **10**, the drag force of which is represented by the vector Q. The other influence is the centrifugal force due to rotation of the apparatus, represented by the vector C. The drag force as discussed above may be represented by the equation $Q=3\pi\nu V_c d$, and similarly the centrifugal force is equal to

$$\frac{\pi}{6}d^3R\omega^2(\rho-\rho_o)$$

If these two forces are equal and opposite then a particle of diameter d will remain motionless at the position P. Particles with a diameter less than d will be accelerated toward the axis of rotation **10** and particles with a diameter greater than d will be accelerated away from the axis **10**. Accordingly this principle of operation may be embodied in apparatus pursuant to the present invention and may be used to separate particles in different size ranges in a faster and more efficient manner than could previously be achieved.

FIGURE 2 schematically illustrates the actual separation of particles in apparatus according to the invention. As in FIGURE 1, the apparatus is rotating about an axis of rotation **10**. The apparatus consists of a lower plate **11**, an upper plate **12** and a baffle **13** which is positioned between the upper and lower plates. The apparatus also includes an area **14** in which the fluid is stagnated and caused to rotate with the members **11** and **12** so that there is no relative motion between the area **14** and the members **11** and **12**. Thus a fluid channel **15**, **16** and **17** is formed with the fluid flowing radially outwardly in the area **15**, vertically in the area **16** and inwardly towards the axis of rotation in the area **17**. It will be noted that the portion of the channel at **16** is narrower than at **15** or **17** and accordingly the flow will achieve its highest velocity in the area marked by the reference numeral **16**. Correspondingly the lowest flow velocity will occur in the area marked by the reference numeral **17**. If a particle suspension is flowing through the channel **15**, **16** and **17** the drag force will be highest in the area **16** and lowest in the area **17**. Preferably the height in the area **17** is one-third of the height in the area **15**. A particle suspended in the fluid and at point P_o would have a velocity indicated by the vector $V_Q \cos \alpha$ which will have an axial component V_Q. It will be appreciated that the particle is not moving directly toward the axis of rotation, however the error introduced is very small and accordingly very little difference in particle size d can be found when calculated according to Equation 3 at radius R2 and R1 respectively. Accordingly a particle with a diameter less than d arriving at point P_o will be directed to the left following the trajectory P_o–P_1 since the drag force Q will be greater than the centrifugal force C. Similarly if a particle of diameter d_2 larger than d arrives at point P_o, the centrifugal force will be greater than the drag force Q and the particle will follow a path P_o–P_2 directed toward the right and away from the axis of rotation. It has been found in practice that Equation 4 may be used directly for calculating the required operating conditions of the apparatus provided that the velocity vector V_Q cosec α of the stream between the points R1 and R2 is 1.412 times greater than the velocity vector V_Q. Under this condition the flow at P_o is larger than V_Q by a factor of approximately 1.412 and Equation 4 may be used in its original form at a predetermined value of R with a good approximation when all other factors of the apparatus are known.

The apparatus of the invention may be constructed in such a manner that Equation 4 can be used to predict the operation of the apparatus, and the flow F, the radius of gyration R at which separation takes place, the number of revolutions per minute N and the diameter d of the particles (considered as spheres) can all be considered as independent variables.

The conditions which must be controlled to give most accurate particle separation are, the dimensions of the separating chamber, the suspending fluid, the dilution of the suspension and the stability of flow.

As explained in the above in relation to FIGURE 2, in order to obtain sharp separation at point P_o and avoid turbulence in the separation zone, baffle **13** should be as thin as possible as well as the spaces between plates **11** and **12** and channel **15** respectively.

Liquids being practically incompressible and considerably more viscous than gasses, they constitute when mixed with particles a more stable system for rotation at high speed and for avoiding turbulence in the separating chamber which would impair the ideal conditions imposed by Equation 4 for proper separation of particles.

As proved by many authors a dilution of 1% or preferably 0.5% weight/volume is of paramount importance in elutriation techniques under gravity or inertial forces. If particles should arrive recombined in the critical zone of separation because of agglomeration they would simply settle at once as particles of larger diameters. A dispersion device accordingly should be used with the present invention. It must be noted here that this condition is difficult to control with air-borne material where agglomeration may be complicated by electric charges built up by friction along the channel walls and by residual moisture especially with particles smaller than 10 microns.

Laminar flow in the separating zone is required because of the almost instantaneous nature of the separation process. The small dimensions of the separating chamber ensure a non-turbulent motion of the liquid and the self feeding and discharging device used with the apparatus of the invention also ensure constant flow. Any drop of pressure in the feeding system can result in a change of velocity of the suspension and impair the separation. In the apparatus of the present invention the pressure difference between any two points selected on a radial plane of the rotating liquid mass will remain constant as long as the angular speed is kept constant; this condition is difficult to realize in the case of a compressible gas suspension moving at high velocity in multi-directional paths.

FIGURE 3 is a cross section, which is partly schematic, illustrating the structure of apparatus in accordance with the present invention. It will be appreciated that the apparatus is circular in plan view being symmetrical about the axis of rotation **10**. As shown in FIGURE 3 the apparatus consists of a base member **11**, a central member **12** and an upper member **18**. The apparatus is provided with a fluid input tube **19** and an outlet tube **20**. The base member **11** is provided with a bore **21** concentric with the axis of rotation **10**, in which a shaft may be positioned to rotate the apparatus. A further bore **22** is provided in which a locking screw may be fitted to lock the apparatus to a shaft inserted in the bore **21**. The base member **11**, central member **12** and the upper member **18** are held together in any suitable fashion such as by bolts **23** passing through holes in the upper and central members **18** and **12** respectively and threaded into holes in the base member **11**. As illustrated in FIGURE 3 O-ring seals **24** and **25** are preferably provided to seal the joints between the central member **12** and the upper and lower members **11** and **18**.

The central member **12** is provided with baffle **13** which corresponds to the baffle **13** in FIGURE 2 around which the fluid suspension is constrained to flow. The passage **26** is provided in the central member **12** through which the fluid passes to the upper member **18** where the particles of a diameter less than the critical diameter and not deposited in the area **14** are coated on the wall **27**. Baffles **28** and **29** are only two of a series of deceleration baffles which are uniformly spaced about the axis of rotation **10** and which serve to prevent the particles deposited in the area **14** and on the wall **27** from being swept away when the apparatus is decelerated after a fluid suspension has been passed therethrough. In actual practice the passageway **26** will not be a continuous cylindrical passageway but will be made up of discontinuous slots or a series of holes through which the fluid flowing around the baffle member **13** may reach the upper member **18**.

The central portion of the member **12** is provided with an upstanding boss **30** through which the stationary water inlet tube **19** protrudes. The interior wall of the boss **30** has an outward and downward slope so that any fluid from the inlet **19** which arrives on the interior wall of the boss will be caused by centrifugal force to flow through the passage **15** and will not migrate back along the outside of the tube **19**. As shown a nut **31** is provided on the outer portion of the boss **30** to clamp the baffle **32** to the central member **12**.

The outlet **20** is provided with a scoop shaped probe **33** which faces toward the direction of rotation of the apparatus and collects the fluid which builds up within the upper member **18** during rotation.

By virtue of the centrifugal action of the apparatus all particles smaller than the critical diameter which are carried through the passage **26** to the upper member **18** are deposited on the inner wall **27** of the member **18** so that only liquid substantially free from particles is picked up by the probe **33**.

The operation of the apparatus illustrated in FIGURE 3 is substantially as discussed in relation to FIGURE 2. The apparatus is rotated about the axis of rotation **10**, fluid is introduced through the inlet **19** thus establishing the predetermined flow rate around the baffle **13** and is recirculated from the probe **33** back to the inlet **19**. The particle suspension to be classified is then introduced into the inlet **19** while maintaining a constant flow rate throughout the system. Particles larger than the critical diameter will be deposited in the area **14** and particles less than the critical diameter will be coated on the wall **27**. The separation of the suspension will take place very quickly. Once the suspension has all been introduced into the inlet **19** the flow of fluid through the apparatus may be stopped and the rotation of the apparatus subsequently stopped. The baffles **28** and **29** will prevent the particles deposited in the area **14** and on the wall **27** from being washed off the wall by the fluid in the decelerating apparatus. Preferably prior to stopping rotation of the apparatus the rotation rate is increased more firmly to coat the particles on the walls of the apparatus and ensure that all particles are at rest before the apparatus is stopped.

FIGURE 4 is a partial cross section of an alternative form of apparatus constructed in accordance with the invention which may be used for performing multiple separations. As before the apparatus is rotated about an axis of rotation **10** and has a lower member **11** and an upper member **18**. A plurality of central members **12**, **12***a* and **12***b* are provided each being associated with a baffle **13**, **13***a* and **13***b* respectively. Collecting areas **14**, **14***a* and **14***b* are also provided in which particles greater than the critical diameter for the flow conditions at the baffles **13**, **13***a* and **13***b* respectively are deposited. By now the operation of the apparatus will be self evident. The largest particles will be deposited in the area **14**, particles of a smaller size will be deposited in the area **14***a*, particles of a still smaller size will be deposited in the area **14***b*, and residual particles will be coated on the wall **27** of the upper member **18**. A nut **31** as before is used to hold the central portion of the apparatus together.

FIGURE 5 is a schematic representation of the use of the apparatus of the present invention. The separator **40** is shown connected by tubing to a flow meter **41**, a three way valve **42** and the dispersion chamber **43**. In accordance with the practice outlined above the separator is caused to rotate at its predetermined rotation rate in accordance with Equation 4. The flow through the separator **40** is adjusted until the proper flow reading is obtained on the flow meter **41** with the fluid flowing between the separator **40** and the flow meter **41** by an appropriate setting of the three way valve **42**. When the appropriate flow is obtained the valve **42** is turned so that the suspension of particles in the dispersion chamber **43** is caused to flow through the separator and the particles are classified. The flow of fluid through the separator **40** may then be stopped by an appropriate setting of the valve **42** and the separator is then accelerated to coat the particles on the walls of the chambers before stopping. The separator may then be stopped and the particles greater than the critical diameter will be found to be separated from the particles less than the critical diameter.

I claim:

1. A centrifugal particle classifier for separating solid particles of different diameters and the same specific gravity into at least two discrete size fractions, said particles being suspended in a liquid, said classifier comprising a rotating portion having a lower plate, an upper plate, and a baffle positioned therebetween, said upper plate, said lower plate, and said baffle being circular, and connected together for rotation about a common axis passing through the centre thereof, a wall connecting the rim of the upper plate to the rim of the lower plate, said baffle being spaced from said upper plate, said lower plate and said wall adjacent the outer end of said baffle to form a flow channel about the end of said baffle and means to cause said liquid with said particles suspended therein to flow laminarly between said lower plate and said baffle in a direction radially away from said axis of rotation, around the end of said baffle and radially towards said axis of rotation between said upper plate and said baffle, particles larger than a predetermined diameter being taken out of suspension and deposited on said wall, and particles smaller than said predetermined diameter remaining suspended in said liquid, said predetermined diameter being dependent on the flow, the specific gravity of the particles, the specific gravity of the liquid, the distance between said baffle and said upper plate, the radius of said baffle, the viscosity of the liquid, and the rate of rotation of said rotating portion.

2. Apparatus according to claim **1** wherein said predetermined diameter is *d*, and wherein the conditions of operation are defined by

$$F=\frac{4\pi^3}{9\nu}(\rho-\rho_o)H(RNd)^2$$

where

F is the flow of said liquid

ρ is the specific gravity of the particles

ρ_o is the specific gravity of said liquid

H is the distance between the baffle and the upper plate

R is the radius of said baffle

ν is the viscosity of the liquid, and

N is the rate of rotation of said rotation portion

3. Apparatus according to claim **1** including deceleration baffles to prevent relative rotary motion between said liquid and said wall.

4. Apparatus as claimed in claim 1 wherein said means to cause flow of said liquid includes inlet means communicating with the flow channel between said lower plate and said baffle for introducing the liquid suspension, and outlet means communicating with the flow channel between the upper plate and the baffle for removing liquid from said apparatus.

5. Apparatus as claimed in claim 4 wherein said inlet means and said outlet means are connected in a closed liquid circuit having two branches, a first branch including a dispersion chamber in which the suspension to be classified may be contained and a second branch including a flow meter for measuring the flow therethrough, said branches being connected by a three way valve permitting flow through either said first or said second branch, or for stopping flow in said circuit.

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