Granulometric and Gravimetric Separation of Microspheres Using Laminar Flow

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ABSTRACT: In this work we present the development of a method and the design of an apparatus for studying the behavior of solid microspheres dispersed in a laminar flow The flows both in up- and down-direction m a vertical glass tube with a circular cross-section were examined In the up-flow experiments rapid lateral migration of the particles was observed towards the tube axis In the down-flow the spheres migrate in the opposite direction towards the wall of the tube A significant dependence on the size of the particles and their relative speed versus the main flow speed was observed This allows the flow to be used for particle separation by size (granulometric separation) and by specific gravity (gravimetric separation)

1 INTRODUCTION

Serge & Silberberg (1962) published their experimental investigations on the flow of suspension of small, freely floating spheres (ı e with the same density as the surrounding liquid) in a tube They found out the extraordinary fact that the spheres are not distributed uniformly across the cross section of the tube, but migrate cross the current lines to a stable equilibrium at a position of 0,6 of tube's radius

Many authors repeated and modified the expenments of Serge & Silberberg (modifying flow type, size and density of particles) obtaining similar result For example, m a flow with a constant gradient (Couette) the particles gather in the middle between the two walls

The theoretical studies suggested the following explanation of the physical nature of the migration force The current of the mam flow ıs Poıseuılle's (with a parabolic velocity profile) Faxen (1922) found out that a solid sphere, which ıs m such a flow, is slow with regard to the surrounding liquid The velocity of the lagging behind is proportional to the gradient of pressure along the tube's length and the square of the sphere's radius The studies of Faxen (1922) and later calculations of Bretherton (1962) showed that for one direction external flow at comparatively small lagging out of the particle the interaction results only m increase of the resistance force in the direction of me main flow In this case no radial displacement along the section of the tube appears

A significant contribution in studying the nature of the effect was performed by Saffman (1965) He demonstrated that at higher relative speeds of the particle, the disturbance which it introduces in the carrying flow spreads at a longer distance and creates a lateral force, which moves the particle perpendicularly to tube's axis At the same time this force is viscosity inert similarly to the interactions m a boundary layer

$$F_L \sim \mu a^2 V(\gamma / v)^{1/2}, \tag{1}$$

where *fi* is the viscosity of the carrying fluid, *a* - sphere's radius, v - relative velocity of the particle with regard to the flow, *y* - speed gradient in the external current

Of course, the presence of walls and other additional disturbances in the carrying fluid will modify the effect It's considered that this is the reason for fixing the particles in the equilibrium position in the experiment of Serge & Silberberg (1962)

At present the theoretical and experimental investigations are concentrated on studying the nature of the migration mainly at neutral floating or for not very heavy particles (Jeffrey & Pearson 1965, Tachibana 1973, Cox & Vasseur 1976)

Regarding the movement of particles with a density significantly different from that of the fluid the theoretical description is not so complete and no experimental studies exist at all. Thus, many authors focused their efforts in this field. The aim of this work is the development of a method of Serge - Silberberg for heavier particles and the study of the migration direction in downstream and upstream laminar flow in a tube.

2 EXPERIMENTAL

The model studies were performed with apparatus presented in Figure 1 (downstream and upstream flow). A given volume of suspension with fixed particle concentration passes at constant speed through a vertical glass tube / with internal diameter $2R$ = 10,10 mm and length l_0 = 120 cm. The tube is connected at both ends with two vessels: feeding vessel *2,* where the stability of the suspension is kept by stirring with stirrer *3* at constant minimal speed and catcher *4* in which the suspension is collected after passing through the tube. The valve 7 switches on/off between the two options I and II of the functioning of the apparatus. This determines the direction of the flow, vertically downward (downstream flow) or vertically upward (upstream flow). At option "downstream flow" the catcher is placed above the level of the feeding vessel in order to eliminate the additional influence of the hydrostatic pressure on the current speed. The movement of the suspension through thé tube in both options is executed by applying negative pressure to the catcher. The negative pressure is provided by a vacuum pump and is preserved constant by a system of two buffers *(10)* - operative and additional - to compensate small changes in the negative pressure occurring during long periods of time. Using the three-way valve (8) the system may be connected to the atmospheric pressure. It is used to transfer back the suspension from the catcher to the feeding vessel due to the established very high-pressure gradient.

The flow velocity in the tube is set and kept constant by araeometer 9 and is controlled by direct reading of the suspension's flow rate *Q,* cm^3/s

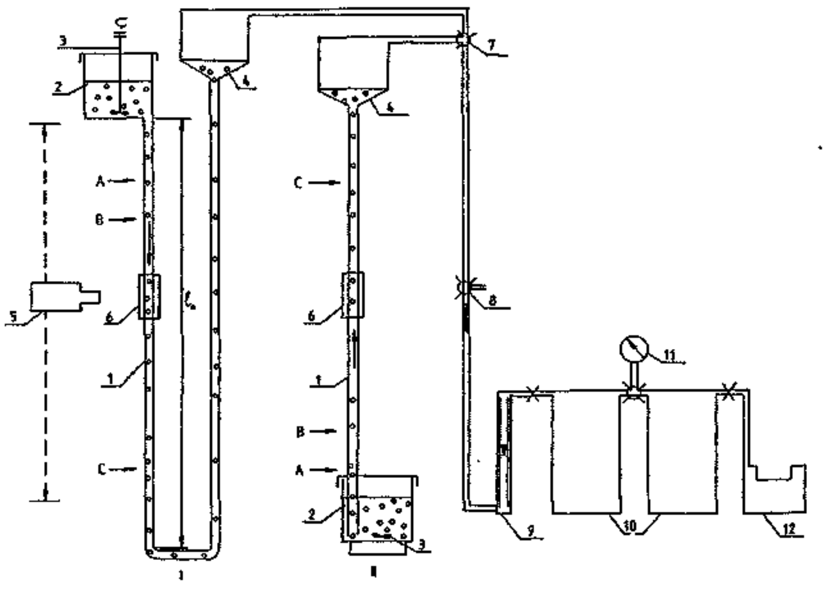

Figure 1 Principle scheme of the apparatus: 1- glass tube; 2 - feeding vessel; 3 - stirrer; 4 - catcher; 5 - horizontal microscope; 6 - cell with plane-parallel walls; 7 - three-way valve for switching on option I or II of the system; 8 - three-way valve for connection with the atmosphere; 9 - areometer; 10 - buffer system; 11 - vacuum meter; 12 - vacuum pump

The behavior of the particles at their movement in the current can be established by determining the particles' concentration distribution at different levels (sections *A*, *B* or C on Figure 1) along the length of the tube in points with coordinates *r* and z, where *r* defines the radial position and coincides with the direction of section's radius of the tube, perpendicularly to the walls, and z is the coordinate coinciding with tube's axis in direction parallel to the walls. By the ratio *r/R* is determined the position of the particles with regard to the axis z.

Certain minimal volume v of the interior of the tube with coordinates *(r,* z) can be focused using a horizontal microscope that can be moved in vertical direction. At a diameter of the vision field Ax = 1,2 mm and at a maximal depth of the focus d_y = 0,05 mm, this volume is

$$v= n(Ax/2)^2 dy = 0{,}018 \text{ mm}^2 \qquad (2)$$

The number N of the particles that pass through the focused minimal volume is read per a unit of time. The obtained values are averaged for 20 measurements at the corresponding mean quadratic error *(a* = ± 0.2 -52 particles depending on *r).* In this way the number of the particles *N* is determined for a fixed section of the tube (z = const), as a function of *r,* and this allow a statistical information on the behavior of a set of particles to be obtained.

The corresponding concentration distribution of the particles *C(r)* is calculated by the dependence *N(r)* according to the formula:

$$C(r) = N(r)/Ax\, dy\, U(r)t, \qquad (3)$$

where *Axdy U(r)* is the volume of the suspension passed through the area *Axdy* with speed *U(r)* for time *t* of reading the number *N(r).*

It is assumed that the speed of the particles in z direction coincides with the speed *U(r)* of the laminar flow that is not affected by the presence of the particles.

According to Poiseuille's law:

$$U(r)=U_{ma}(l-r^z/B?) \qquad (4)$$

where U_{max} is the speed of the flow along the axis of the tube.

The measurements at two relatively perpendicular diameters of the section *x* and *y* and at the intermediate radial positions show symmetrical distribution of the particles around the tube's axis, i.e. the obtained results confirm the reference data for symmetry of the flow (Segre & Silberberg 1962, Jeffrey & Pearson 1965).

According to reference data, the main parameters determining the trajectory of a particle in a flow are the Reynolds's number of the tube *Re,,* the ratio of particle's diameter to the diameter of the tube and the ratio of sedimentation speed of the particle by Stokes to the maximal speed of the flow. The physical variables defining the flow in any moment of time, which may be used in general for experimental studies are the radius of the tube *R,* the particle's radius *a,* the flow speed along the axis of the tube $U_{,,lax}$, the viscosity of the suspension *fi,* the fluid density *P/* , the particle density *pp,* and the cylindrical coordinates (V, z).

For laminar flow *Re,* = $PfU_{max} R/ß$ < 23

The model experiments were carried out under the following conditions. It was used a suspension of glass microspheres with dimensions *2a* = 50 *jum* and *Pp* = 2,38 g/cm^3 in a media of monodistilled water with initial concentration C_0 = 50 part/cm^3. The behavior of the particles during their movement in the tube is observed at flow rate of the suspension *Q* = 4 cm^3/s, average speed of the flow *U* = Q/nR^2 = 5 cm/s, and corresponding maximal speed U_{mm} ~ 10 cm/s. This maximal value of the flow's speed was confirmed by the introduction of colorant fine insoluble particles and reading the speed of movement at the top of the obtained profile of the laminar flow in the tube. Under these conditions *Re,* is 500.

The speed of the flow is set and maintained constant by negative pressure *P,,* = -83,4 kN/m^2. The time for reading the number of ballots *N* passed through the envisaged minimal volume is 1 minute.

The suspension is stirred with minimal speed of the stirrer (350 rev/min) to achieve good dispersion of the particles in the volume without forming bubbles. The lack of bubbles in the system under these experimental conditions was proven by a zero experiment, where an observation of the flow without ballots was performed.

At flow of the suspension in the beginning of the tube it is observed a section with chaotically moving particles due to the stirring in the feeding vessel. The experimentally established length / of this section for the flow upwards is 13 cm, and for the flow downwards is 14,5 cm.

The registration of the passed ballots trough the observed minimal volume at both options of the model experiment - upstream and downstream is taken at levels *A* (z = 0), *B (z* = 3 7 cm) and *C (z* = 77 cm), where z = /,, - *A,* i.e. *A* corresponds to the end of the chaotic movement of the particles along the section of the tube.

3 RESULTS AND DISCUSSION

It was determined the dependence of the number of ballots passed through the minimal observed volume per unit of time as a function of the radial coordinate r at z = const, as well as the respective concentration distributions $C(r)$, calculated according to formula (3).

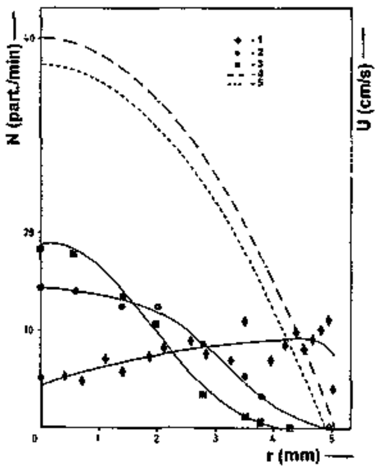

Figure 2. Dependence of the number N of passed particles as a function of radial coordinate r for an upstream flow: Î - at level A (z - 0 cm); 2 - at level B (z = 17 cm); at level C(z = *11* cm); 4 - profile of velocity of a flow $U(r)$; 5 - relative speed of movement of ballots along the axis z:$Vj(r) = U(r) - V_{,,d}$

Figure 2 shows the distribution of the particles at levels A, B and C for the upstream flow of *N^(r), Ns(r) and Nc(r).* On the same figure are presented the profile of speed of the flow $U(r)$ and the profile of the speed of movement of the ballots in the flow considering the speed of lagging behind according to Stokes: $V = U(r) - V_{,ei}/$. In this way it is determined the width of the zone free of particles next to the tube wall formed only due to sedimentation (Ar = 0,2 mm).

If the concentration C of the particles at their flow through the tube is constant along r, the number of particles N passed through a given point per unit of time is proportional to the speed of the suspension flow at the same point. As the speed $U(r)$ has a parabolic distribution across the section of a tube for a laminar flow, the number of the particles passed $N(r)$ is also distributed according to a parabolic law.

For neutrally floating particles (Ap = 0) such parabolic distribution was located at a small distance above the inlet of the tube, after which many different distributions are observed till forming a peak at r/R = 0,6 (Segre & Silberberg 1962).

For heavy particles (Ap > 0) the place z of even distribution of the concentration along r is more difficult to be established. Due to the need of more intensive stirring in the feeding vessel, the concentration of the particles at their entering into the tube is higher near the walls and they have some non-rectilinear movement there, influenced by the direction of rotation of the stirrer. For this reason *C/i,r)* has the trend shown on Figure 3. In addition the speed of the cross migration is comparatively high and the particles near the tube's axis start to migrate more rarely (at lower value of *z)* then those next to the wall.

At level B the function $N_B(r)$ has the nature of a parabola near the axis, but next to the walls, even after determining the width of the free zone due to particle sedimentation is formed a zone with decreased concentration of particles because of migration. The effect is even more expressed at level *C-Ndr).*

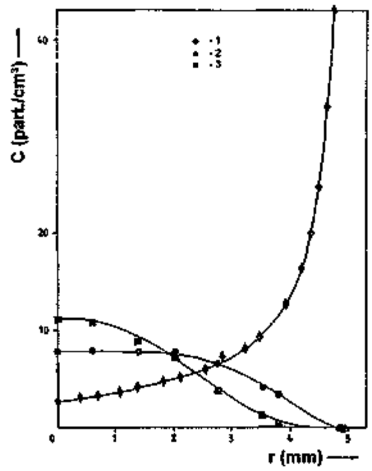

Figure 3. Distribution of the concentration C as a function of the radial position for an upstream flow: / - for level A (z = 0 cm); 2 for level B (z = 17 cm); for level C (z = 77 cm)

In Figure 3 are presented the concentration distributions of the microspheres at levels A, B and C - $C_A(r)$, $Ca(r)$ and $Cc(r)$ for an upstream flow. The obtained distributions of ballots as a function of r definitely prove the cross migration of heavy particles (Ap = 1,38 g/cm^3) under the conditions of upstream laminar flow in direction to the tube axis.

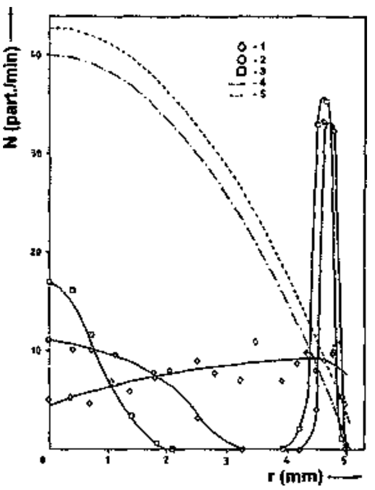

Figure 4. Dependence of the number N of passed particles as a function of the radial coordinate r for downstream flow: *1* - for level *A (z* = 0 cm); 2 for level *B* (z = 17 cm); for level *C(z* = 77 cm); 4 - flow's velocity profile *U(r);* 5 - relative velocity of ballots' movement in the current along the axis z $V_z(r) = U(r) - V_{sed}$

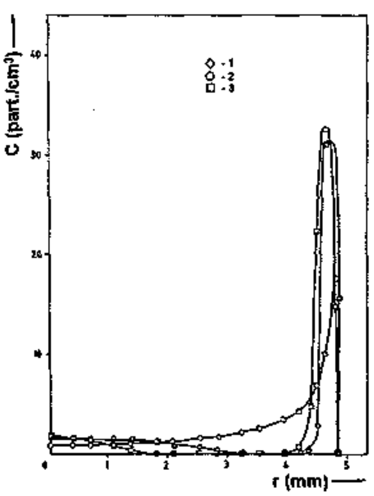

Figure 5. Distribution of the concentration C as a function of the radial position r for a downstream flow; / - for level *A* (z = 0 cm); 2 for level *B(z=\l* cm); for level *C (z* = 77 cm)

Figure 4 shows the distributions of ballots *N(r)* at levels A, *B* and *C* for downstream flow and on Figure 5 are shown the respective concentration distributions *Crfr), Ce(r)* and *Ccir).*

The cross migration of the particles in direction to the walls of the tube is clearly visible. At distance between 0,1 and 0,5 mm from the walls (level *B)* and between 0,2 and 0,6 mm (level *Q* is observed highly increased particle concentration. A zone free from particles is formed with a width of 0,9 mm at level *B (r/R* = 0,65 to 0,83), which increases with 1 mm *(r/R* = 0,4 to 0,77) when the length of the travel increases to level C.

The results obtained here for downstream and upstream flows are in agreement with the observations of Jeffrey & Pearson (1965). An attempt for quantitative evaluation is made by Cox & Vasseur (1976), but the calculations were done at heavy initial assumptions, which in the investigated case are not met. The form of the solutions obtained there does not present a clear physical idea for the mechanism of the phenomena. This is a specific combination of the effect of the walls, the difference in the density of the particles and the fluid *Ap* and the character of the main flow.

It is forth a further investigation of the displacement of the maximum in the concentrations distribution across the cross section depending on *Ap.*

Near the tube axis at downstream flow is observed some increasing of ballots concentration, which according to the reference data hasn't been observed until now. This effect is not predicted by the theory and has no explanation at the moment.

4 CONCLUSIONS

1. A method and apparatus for studying the behavior of heavy particles under the conditions of laminar flow in a tube with circular cross section were elaborated.
2. The conducted model investigations with glass microspheres demonstrate definitely the presence of comparatively fast cross migration. Under the conditions of upstream flow this migration is in the direction to the tube axis. Under the conditions of downstream flow it is established a strongly increased concentration along the walls, the formation of a free of particles zone at *r/R* = 0,4 to 0,8 and a particle concentration around the tube axis.
3. The study performed in this work might have significant practical application. The observed dependence on the size of the particles and on

their relative speed with regard to the main flow allows its application to classification of materials by size (granulometric separation) and by specific weight (gravimetric separation).

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