Light-induced sedimentation in nanoliquids

G Ivanova, V Khe and V Ivanov
Far Eastern State Transport University, 21 Seryshev Str., Khabarovsk, 680000, Russia
khe@ngs.ru

Abstract. We have discussed the theoretical model of sedimentation of nanoparticles by using
the laser effect in liquid. It was received the steady-state solution of one-dimensional task of
the light induced mass transfer as depending on intensity of laser beam. It is shown that it can
allow to divide polydispersive mixtures. The proposed model of sedimentation of nanoparticles
is relevant in the study of dispersed liquid-phase media, as well as in the optical diagnostics of
such materials.

1. Introduction
Processes of sedimentation are ubiquitous in nature and important for science and technology. Gravity
settlers are commonly used to separate particles from waste streams and, in lab practice, analytical
ultracentrifugation is a common tool to separate or characterize particle size distribution. Besides their
practical interest, sedimentation studies on model systems have also provided fundamental information
on the structural properties of colloidal suspensions [1].

In a gravitational field, only sufficiently large particles that are not subject to thermal (Brownian)
motion are capable of precipitating. The steady-state deposition rate of the particles depends on the
mass, size and shape of the particles, viscosity and density of the medium. In this case, the larger the
mass and the particle size, the higher the settling velocity. For smaller particles, for example,
molecules of natural and synthetic polymers, centrifugation is usually used [2-3]. Separators, working
on the basis of the above methods, are quite bulky (large-sized) in the execution of the design. We
suggest using light pressure forces for the sedimentation of nanoparticles in a liquid. These forces have
a sufficiently large value, providing a sedimentation rate comparable with centrifugal methods.
This paper is devoted to the model of sedimentation of nanoparticles by a light field, which is an
alternative to the above methods, which makes it possible to create compact separators of small
particles.

2. Light-induced sedimentation
Consider the liquid phase medium with the nanoparticles (dispersed phase) which is under the
influence of the reference laser beam with a uniform intensity profile $I$ (figure 1).

Light pressure force acting on the nanoparticle from the high-power reference beam is equal to[4]:

$$F_p = \frac{128\pi^3 \alpha^6 n_2}{3c_0\lambda^4} \left[ \frac{m^2 - 1}{m^2 + 2} \right] I$$

(1)

where $m=n_2/n_1$, $n_2$, $n_1$ are the refractive substance indices of the dispersion medium and the dispersed
phase respectively, $c_0$ is velocity of light, $\alpha$ is particle radius, $\lambda$ – light wavelength.
Balanced one-dimensional equation describing the dynamics of the concentration of the nanoparticles in a liquid phase medium with diffusion[4]:

\[
\frac{\partial C}{\partial t} = D \nabla^2 C - V \nabla C .
\] (2)

Figure 1. The light-induced sedimentation scheme: 1 – cell with liquid, I – laser beam.

Here \( C(z,t) \) is volume concentration of particulate matter, axis \( z \) is aligned with the reference beam \( I \), \( D \) is diffusion coefficient; particle velocity \( V=(64\pi^2 a^2 n_1 (m^2 - I) (m^2 + 2)^4 (9c_0\lambda^4\eta)^{-1}) \), where \( \eta \) is viscosity of the fluid.

The relevant boundary conditions:

\[-D \nabla C + \vec{V}C = 0 , \text{ when } z = 0 \text{ and } z = l , \] (3)

Where \( l \) is the height of the cell along the propagation of the reference beam.

Initial conditions:

\[ C = C_0 , \text{ when } t = 0 , \] (4)

where \( C_0 \) is the initial concentration of nanoparticles.

For the steady-state solution of the equations (2)–(4):

\[ C(z) = C_0 \gamma D^{-1} I \frac{e^{\gamma D^{-1} z}}{e^{\gamma D^{-1} l} - 1} . \] (5)

The expression (5) can be written as the concentration of particles on the radiation intensity and height:

\[ C(z, I) = C_0 \gamma D^{-1} I \frac{e^{\gamma D^{-1} z}}{e^{\gamma D^{-1} l} - 1} , \] (6)

where \( \gamma = 64\pi^2 a^2 n_1 (m^2 - I) (m^2 + 2)^4 (9c_0\lambda^4\eta)^{-1} \).

The expression (6) we can write as:

\[ C(z, I_{ph}) = C_0 l \frac{e^{\gamma D^{-1} z}}{e^{\gamma D^{-1} l} - 1} , \] (7)

where we introduce parameter \( l_{ph} = D/\gamma I \), that shows the depth at which the particle concentration changes by a factor of \( e \) at a given intensity.
The figure 2 illustrates the dependence of the parameter $l_{ph}$ on the radiation intensity for the following values: $a=10^{-7}$ m, $n_1=1.1$, $n_2=1.33$, $\lambda=632$ nm, $\eta=1.004\cdot10^{-3}$ Pa$s$.

**Figure 2.** Dependence of the parameter $l_{ph}$ on the radiation intensity.

Also the expression (6) can be written as:

$$C_{r,u}(z',I_{r,u}) = \frac{I_{r,u}}{I_0} \frac{\exp(I_{r,u} z')}{\exp(I_{r,u})-1},$$

where $C_{r,u}(z',I_{r,u})=C(z,I)/C_0$ is relative concentration, $I_{r,u}=I/I_{sat}$ is relative intensity of radiation, $I_{sat}=D/\gamma l$ is saturation intensity, $z'=z/l$.

In the sedimentation analysis the important molecular-kinetic characteristic of system is the sedimentation constant $S$ (Svedberg) that is equal to the ratio of the sedimentation rate to the centrifugal acceleration:

$$S = \frac{V}{\omega^2 R} = \frac{2a^2 \Delta \rho}{9 \eta},$$

where $\omega$ is angular velocity of the centrifuge, $R$ is centrifugal radius, $\Delta \rho = \rho_p - \rho_m$ is particle density, $\rho_m$ is density of medium.

The sedimentation constant depends on the mass, the shape of the particles and the phase. 1 Svedberg has the dimension of time and is numerically equal to $10^{-13}$ seconds.

By analogy with the sedimentation constant, we introduce a quantity $S_L$ characterizing the sedimentation in a light field:

$$S_L = \frac{V}{F_p \left( \frac{4}{3} \pi a^3 \rho_p \right)^{1/3}} = \frac{2a^2 \rho_p}{9 \eta}.$$  \hspace{1cm} (10)

It is seen that the advantage of introducing sedimentation constant in a light field is the absence of dependence on the density of the medium.

Figure 3 shows the dependence of the angular velocity of a centrifuge on the intensity of radiation required to attain the same sedimentation rate as in ultracentrifugation at the following values: $a=10^{-7}$ m, R=0.1 m.
Another feature of our model is the strong dependence (radius of the 5th degree) of the deposition rate on the particle radius, which, in our opinion, can allow much more efficient diagnostics of mixtures of polydisperse particles.

![Graph showing angular velocity dependence on intensity of radiation](image)

**Figure 3.** Dependence of the angular velocity of a centrifuge on the intensity of radiation.

3. Conclusion
Expression (8) gives a direct relationship between the change in the relative concentration and the relative intensity of radiation at the bottom of the cell. As estimates show, an increase in the relative concentration requires an intensity of about 1 MW/m$^2$, which, however, is achievable for transparent nanomaterials using continuous laser sources.

Thus, an optical method for the sedimentation of particles from suspension is proposed. A distinctive feature of the method is the use of light pressure forces, with the help of which it is possible to carry out effective sedimentation of nanoparticles in a transparent medium.

The parameter $l_{ph}$, characterizing the variation in the concentration along the cell height, is analyzed as a function of the radiation intensity.

The proposed model of optical sedimentation of nanoparticles is relevant in the study of disperse liquid-phase media, and, also, for optical diagnostics of such media, as an alternative to the centrifugation method.

References
[1] Buzzacco S, Tripodi A, Rusconi R, Vigolo D and Piazza R 2008 *Journal of Physics: Condensed Matter* **20** 494219
[2] Rabinovich G D 1981 *Separation of isotopes and other mixtures by thermal diffusion* (in Rus.) (Moscow: Atomizdat) p 144
[3] Schuck P 2000 *Biophys. J.* **78** 1606
[4] Ivanov V, Ivanova G, Krylov V and Khe V 2016 *Proceedings of SPIE* **10176** 1017607