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Aggregation in colloidal suspensions: Effect of colloidal forces and hydrodynamic interactions

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ABSTRACT

The forces acting in colloidal suspensions and affecting their stability and aggregation kinetics are considered. The approximations used for these forces in numerical simulations and the importance of the balanced account for both colloidal forces and hydrodynamic interactions are discussed. As an example the results of direct numerical simulations of kinetics of aggregation either with account for hydrodynamic interaction between particles or without it are compared by varying the parameters of the interaction potential between particles and fraction of solid. Simulations are based on the Langevin equations with pairwise interaction between particles and take into account Brownian, hydrodynamic and colloidal forces. It is confirmed that the neglecting of hydrodynamic interaction results in an accelerated growth of aggregates. The results of numerical simulations of aggregation kinetics are compared with well known analytical solutions.

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1. Introduction

Aggregation in colloidal dispersions, suspensions and emulsions, is important for many natural phenomena and industrial processes. Stability in these systems is determined by the relation of attractive and repulsive forces acting between particles [1–3]. If attractive forces (van der Waals forces or/depletion interaction in the dispersion medium containing a non-adsorbing polymer) prevail, particles coagulate irreversibly in the deep primary potential well, forming large aggregate with fractal structure, characterized by the power law dependency of mass of the aggregate M on the radius of gyration Rg:

\[ M \sim R_g^{d_f}, \]  

where \( 1 < d_f < 3 \) is the mass fractal dimension. In the absence of long-range repulsive forces the aggregation kinetics is diffusion limited (DLCA) [7] with typical value of the mass fractal dimension about 1.8.

If the repulsion is included, for example, due to electrical charge on particle surfaces or adsorbed on their surface polymer, then potential barrier appears complicating aggregation. In the latter case not each collision of two particles results in their aggregation. Aggregation slows down being reaction limited (RLCA) [8]. Particles have more time for the rearrangement inside the aggregate, therefore RLCA results in formation of denser aggregates in comparison with DLCA, with the mass fractal dimension about 2.1. The probability of sticking decreases with the increase of the height of the potential barrier and when repulsion is strong enough, dispersion becomes kinetically stable, i.e. particles do not aggregate during a long period of time.

In the presence of both, attraction and repulsion, between particles a colloidal dispersion can reveal a more complicated behavior than the only either kinetic stability or irreversible coagulation. The reversible coagulation in the relatively shallow secondary potential well [9,10] can result in formation of aggregates of finite size in dynamic equilibrium with singlets, especially when the potential barrier between primary and secondary potential well is high enough to prevent the jumping of particles into the primary potential well. The average size of aggregates is determined by the dynamic equilibrium between aggregation due to attraction between particles and disaggregation due to their thermal motion and should therefore depend on the depth of the secondary potential well. If the latter is large enough, then the irreversible aggregation with an unlimited growth of aggregates occurs even in the secondary potential well [11]. It has been assumed, that there can be also other mechanisms resulting in the formation of stable aggregates of colloidal particles, which stop to grow after reaching a certain size, when the long range repulsion between colloidal particles compete with attraction [12–14]. Formation of phase of stable clusters in equilibrium with singlets has been observed in many investigations [15–23] employing different experimental techniques, including direct observations by confocal microscopy [19–22].

The clear understanding and correct prediction of aggregation kinetics and mechanisms responsible for formation of stable aggregates as well as estimation of equilibrium size of aggregates on the
basis of properties of dispersed particles and dispersion medium is of
great importance, as aggregation can change drastically the physical
properties of colloidal dispersion, in particular its rheology [24–29].

Below the forces coming into play in colloidal dispersions and
determining either their stability or aggregation kinetics are reviewed
in the relatively shallow potential well, with depth of up to 20 kT. Some
original results of numerical simulations are used along with
published data to illustrate the effect of fraction of solid, potential
well characteristics and hydrodynamic interactions on aggregation
kinetics and equilibrium aggregates size in the case of reversible
aggregation.

2. Numerical modelling and representation of forces acting in
colloidal suspensions

One of the most powerful tools to study aggregation processes in
colloidal suspensions is numerical simulations. There are a number of
simulation methods developed, enabling simulations of kinetics
and/or equilibrium properties. Well-known examples are Monte–
Karlo [30–32], molecular dynamic [13,33] and their modifications,
dissipative particles dynamic simulations [34] as well as numerical
solution of population balance equations [35–38]. Below we focus on
another widely used method which is highly suitable for studying of
aggregation kinetics, the Brownian dynamic simulations [39–42]. The
latter method is based on the numerical solution of Langevin
equations [43–46]. This method enables a direct simulation of time
evolution of ensemble of particles immersed in a dispersion medium
considered as a structureless continuum with a defined viscosity. The
review of Monte–Karlo, molecular dynamics and Brownian dynamics
modeling techniques is given for example in [47,48].

The crucial step in the Brownian dynamic simulations is a proper
choice of forces acting on particles and between particles. On the one
hand, a certain simplification of model is required to get the
reasonable simulations time, but on the other hand, the model has
to retain the essential physics of real systems. The DLVO theory [1–3]
provides a good basis for description of colloidal forces between
particles. Usually particles are considered as being identical and
spherical and forces between them pairwise additive. Most commonly
the London–van der Waals dispersion forces are used for attraction
[24,49–51]:

\[ U_{\text{vdw}} = \frac{A}{6} \left[ \frac{2\alpha^2}{h(4a + h)} + \frac{2\alpha^2}{(2a + h)^3} + \ln \frac{h(4a + h)}{(2a + h)^2} \right], \]

where \( A \) is Hamaker constant, \( a \) is the particle radius, \( h \) is the surface
between particles, and electrostatic double layer interaction for repulsion [24,49–51]:

\[ U_{\text{el}} = \frac{2n_e\Phi_0^2 2a}{2a + h} \exp \left( -\frac{\kappa h}{\kappa a < 5} \right), \]

\[ U_{\text{el}} = 2n_e\Phi_0^2 2a \ln \left( 1 + \exp \left( -\frac{\kappa h}{\kappa a > 5} \right) \right), \]

where \( \varepsilon = \varepsilon_m \varepsilon_0 \) is the permittivity of the medium, \( \varepsilon_0 \) is the permittivity
of vacuum and \( \varepsilon \) is the relative permittivity or dielectric constant, \( \Phi_0 \) is
the surface potential of particles, \( \kappa^{-1} \) is the Debye screening length.
For \( z^2 \) electrolyte

\[ \kappa = \left( \frac{e^2 T}{2\pi^2 \varepsilon^2 n_b} \right)^{-1/2}, \]

where \( k \) is the Boltzmann constant, \( T \) is the temperature and \( n_b \) is the number
of ions in the bulk.

Here the aggregation of colloidal particles in the relatively shallow
potential well is of the main interest, in particular, aggregation in the
secondary potential well. The usual distance of the secondary
potential well to the interface is of the order of 10–100 nm [52].
That means that by rigorous consideration of the problem the
retardation of dispersion forces should be taken into account. The
comprehensive discussion on retardation problem is given in [47,52].
Retardation means that the Hamaker constant \( A \) in Eq. (2) in reality
is not a constant, but decreases with the increase of the distance to the
surface of a particle. For example, according to the results of numerical
simulations [53] the value of Hamaker constant for gold in water
decreases about twice by the increase of separation from 1 to 20 nm.
The values of Hamaker constant given in reference books are those for
small separations, where retardation is negligible. Therefore, by using
them the depth of the secondary potential well is overestimated, as
shown in Ref. [52], Fig. 1.15.

Other forces which can come into play are as follows. Depletion
attraction due to presence of non-adsorbing polymer [54] (or
nano-particles) can be calculated as [24]:

\[ U_0 = -\frac{4m(a + \delta)^3}{3} \left( 1 - \frac{3(2a + h)}{4(a + \delta)} + \frac{(2a + h)^2}{16(a + \delta)^2} \right) \Pi \quad \text{at} h < 2\delta, \]

\[ U_0 = 0 \quad \text{at} h > 2\delta, \]

(6)

where \( \delta \) is the equivalent-hard sphere radius of depleting species, \( \Pi \) is the
osmotic pressure in the bulk. For ideal solutions \( \Pi = \rho kT \), where \( \rho \)
the number density of macromolecules. However, if non-ideality of
the polymer solution is taken into account then:

\[ \Pi = \rho kT \left( 1 + \frac{2nM}{\rho_m N_a} \right), \]

(7)

where \( N_a \) is the Avogadro number, \( M \) is the mean molecular weight of
polymer and \( \rho_m \) its mass density, \( n \) is number density.

The repulsive hydration energy \( U_{\text{hyd}} [1,24,55]: \)

\[ U_{\text{hyd}}(h) = \pi a \lambda^2 P_0 \exp \left( -\frac{\kappa h}{\lambda} \right), \]

(8)

where \( \lambda \) is the decay length (usually in the range 0.2–1.1 nm for 1:1
electrolytes), and \( P_0 \) is the hydration pressure constant, which
increases with materials’ hydrophilicity.

The energy of structural repulsion in the case of particles covered
by polymer can be estimated as [2,24]:

\[ U_{\psi}(h) = kT \frac{160aL^2}{m^3} \exp \left( -\kappa h / L \right), \]

(9)

(10)

where \( L \) is the thickness of attached polymer chains, \( s \) is the average
distance between the chain attachment points at the surface of
particle.

The particles can encounter each other because they move with
different velocities in the dispersion medium. Here we consider the
case without any imposed flow. The small particles are then in
random Brownian motion and aggregation is called perikinetic. When
the particles size is large enough the gravitation should be taken into
account. In a polydisperse suspension large particles move with
different velocities depending on their size (differential sedimen-
tation) and aggregation is called orthokinetic. The effect of gravity on
the aggregation of suspensions is discussed in details in Ref. [56].

The relative importance of Brownian motion and sedimentation is
determined by the Péclet number:

\[ Pe = \frac{2n_\text{Pe}_0 a^4}{3kT}, \]
where $\Delta \rho$ is the density difference between dispersed material and dispersion medium, $g$ is the acceleration due to gravity. When $Pe \ll 1$ Brownian motion dominates and aggregation is pure kinetically, whereas at $Pe >> 1$ aggregation is mainly orthokinetic, due to differential sedimentation. By taking $Pe = 1$ the critical diameter of particles can be estimated as about 1–3 mm depending on $\Delta \rho$.

If aggregation occurs in the secondary potential well, particles can jump over the barrier into primary potential well [57,58]. In this case all particles eventually will be aggregated irreversibly. Only if a potential barrier is high enough aggregation can be considered as a reversible.

It is obvious that Eqs. (2)-(9) are rather complicated and their direct implementation into numerical schemes will result in the considerable increase of computational time. That is why simplified representations of interaction potentials are often used, such, for example, as Lennard–Jones potential describing attraction and steric repulsion [13,14,48]:

$$U_{ij}(h) = 4 \varepsilon_{ij} \left( \left( \frac{a}{h + a} \right)^{12} - \left( \frac{a}{h + a} \right)^{6} \right),$$

(11)

where $\varepsilon_{ij}$ is the characteristic potential energy minimum; or Yukawa potential for a long-ranged repulsion [13,14]:

$$U_{ij}(h) = \alpha_{ij} e^{-h/a} \frac{h}{h + a},$$

(12)

where $\alpha_{ij}$ and $\xi$ are parameters.

However, the combination of potentials (11) and (12) does not produce the secondary potential minimum [14], which is of interest below.

Sometimes for a simplification the colloidal forces are omitted at all, but replaced by an approximation of sticky particles, aggregated irreversibly when interparticle separation becomes smaller than certain arbitrary chosen value, i.e. approximation of square potential well of infinite depth [59]. It seems, however, that such approximation is too rough, especially for kinetic studies, because particles begin to feel each other only at the moment, when they stick together.

Much more promising approximation for colloidal forces has been used in [60,61], where colloidal forces $F(h)$ were modelled instead of interaction energy as:

$$F(h) = C \frac{(h-h_1)(h-h_2)(h-h_3)}{h^5},$$

(13)

where $h_1$, $h_2$, $h_3$ are positions where the force is equal to zero; $C$ is a constant depending on the particles sizes and physicochemical properties of components of dispersion. The colloidal forces modeled in such way are similar to the real colloidal interaction forces having three intersection points with abscissa axis corresponding to equilibrium positions. A similar approach is used in the presented study enabling to investigate the dependence of aggregation kinetics not only on the depth of potential well, but also on the shape of the energy curve.

The conservative forces acting between particles are not only ones affecting the kinetics of aggregation. It has been shown [48,62,63], that hydrodynamic interactions between particles slow down the aggregation, i.e. a reasonable approximation for hydrodynamic interaction is vital for the adequate description of aggregation kinetics. Unfortunately, calculation of the full tensor of hydrodynamic friction coefficients or mobility tensor, which is mainly used in the Brownian dynamic simulations is unrealistic. The elements of mobility tensor have been tabulated only for the case of two equal particles [64]. That is why in many numerical studies the hydrodynamic interactions are neglected at all and hydrodynamic resistance to the particle motion is assumed to be constant and independent of presence of other particles [59,65,66]. The comparison of simulation results for two interacting particles using either mobility tensor proposed in [63] or Oseen approximation has shown that at close separation the Oseen tensor overestimates greatly the tendency of two spheres to move towards each other [67].

A good compromise has been proposed in [68], where it has been shown that a mobility tensor calculated by taking into account the hydrodynamic interactions between nearest neighbors in the lubrications approximation, assuming pairwise additivity of these interactions retains the essential physics of aggregation process. This approach was developed further in [69,70] employing in the numerical scheme calculation of the hydrodynamic resistance coefficients instead of mobility tensor. This enabled to avoid the matrix inversion. Below, as an example, the mathematical model and numerical scheme developed in [69,70] is used to study the effect of fraction of solid, colloidal forces and hydrodynamic interactions on kinetics of aggregation in colloidal suspensions.

3. Mathematical model

The detailed description of the model is given elsewhere [69,70] therefore below are presented the only main points. We consider 2D suspension composed of $N$ identical particles in a Newtonian dispersion medium. The motion of each particle is governed by Langevin equation [43–46]:

$$m \frac{d\mathbf{v}_i}{dt} = -2N \sum_{j=1}^{N} C_{ij} \mathbf{v}_j + \sum_{j=1}^{N} \alpha_{ij} \mathbf{f}_j + \sum_{j=1}^{N} \mathbf{F}_j,$$

(14)

where $i = 1...2N$, $m = \frac{4}{3} \pi a^3 (\rho_p + 0.5\rho_l)$ is the mass of the particle (including the added mass), $\rho_p$ is the density of the particle material, $\rho_l$ is the density of the suspending liquid, $V$ is the particle velocity, $C_{ij}$ is the element of the hydrodynamic resistance tensor, $\alpha_{ij}$ represents the Brownian forces, with $f_j$ being a random quantity, normally distributed, with

$$f_i = 0,$$

(15)

$$f_i(t) \delta(t-t') = 2 \pi \delta(t-t'),$$

(16)

and $F$ represents the colloidal forces.

The matrix of hydrodynamic resistance coefficients and matrix of Brownian coefficients are correlated according to the fluctuation–dissipation theorem [39]:

$$C_{ij} = \frac{1}{kT} \sum_f \alpha_{ij} \xi_{ij}.$$

(17)

It is assumed below that all forces, including hydrodynamic forces, are pairwise additive, and for any pair of particles the hydrodynamic interaction depends only on the distance between them and their relative velocities.

The most important for the aggregation processes are hydrodynamic interaction at short distances between particles, where also colloidal forces come into play. To model them, the lubrication approximation derived in [71] is used for small separation between particles $h \leq 0.1a$.

$$C_x = \frac{3}{2} \pi \mu a^2,$$

(18)

$$C_y = \pi \mu a \ln \left( \frac{a}{h} \right),$$

(19)

where $\mu$ is the dynamic viscosity of the suspending liquid, local x axis is directed along particles center to center line, y axis in perpendicular direction. It is assumed that the hydrodynamic interaction becomes
negligible at \( h > 2.5a \) and in this case \( \varsigma \) is a scalar determined by Stokes law:

\[
\varsigma = 6 \pi \eta a.
\]  

(20)

The interaction forces for \( 0.1a \leq h \leq 2.5a \) were fitted by polynomials to enable a smooth transition over the whole hydrodynamic interaction region. Eq. (19) was also fitted by a polynom to simplify numerical procedure.

Then the matrix of hydrodynamic resistance for two interacting particles can be written as:

\[
\hat{\varsigma} = \begin{pmatrix}
\varsigma + S_x & 0 & -S_x & 0 \\
0 & \varsigma + S_y & 0 & -S_y \\
-S_x & 0 & \varsigma + S_x & \varsigma + S_y \\
0 & -S_y & 0 & \varsigma + S_x
\end{pmatrix}
\]  

(21)

with \( S_x, S_y \) and \( \varsigma \) given by Eqs. (18)–(20).

The matrix of Brownian coefficients has the same form as the matrix of hydrodynamic coefficients:

\[
\hat{\alpha} = \begin{pmatrix}
\alpha_{11} & 0 & \alpha_{13} & 0 \\
0 & \alpha_{22} & 0 & \alpha_{24} \\
\alpha_{13} & 0 & \alpha_{11} & 0 \\
0 & \alpha_{24} & 0 & \alpha_{22}
\end{pmatrix}
\]  

(22)

with

\[
\alpha_{11} = \frac{1}{2} \sqrt{kT} (\sqrt{\varsigma + \varsigma + 2S_x})
\]

\[
\alpha_{13} = \frac{1}{2} \sqrt{kT} (\sqrt{\varsigma - \varsigma + 2S_x})
\]

\[
\alpha_{22} = \frac{1}{2} \sqrt{kT} (\sqrt{\varsigma + \varsigma + 2S_y})
\]

\[
\alpha_{24} = \frac{1}{2} \sqrt{kT} (\sqrt{\varsigma - \varsigma + 2S_y})
\]

(23)

The random functions \( f_i \) were modelled as [72,73]:

\[
f_i = \frac{\sqrt{2}}{dt} R_{ND}
\]  

(24)

where \( dt \) is the time step to be chosen for numerical simulations, \( R_{ND} \) is a random number from a normal distribution with mean value equal to zero and standard deviation equal to 1.

To model colloidal forces the simplified linear expression with parameters \( h_1, h_2, h_0 \) and \( U_{min} \)-corresponding to the depth of potential well, has been used for the dependency of normal force per unit area between two parallel flat surfaces, \( \Pi(h) \), on distance between them:

\[
\Pi = \frac{2 U_{min}}{nK} \frac{h_1 - h}{h_1 - h_0} \quad 0 \leq h < h_0,
\]  

(25a)

\[
\Pi = \frac{2 U_{min}}{nK} \frac{h_2 - h}{h_2 - h_0} \quad h_0 < h < h_2,
\]  

(25b)

where

\[
R = \frac{S^2}{3(h_1 - h_0)} + \frac{(h_2 - h_0)^2 - (h_1 - h_0)^2}{3} + (h_2 - h_1)(S + h_0 - h_1)
\]

and

\[
S = \sqrt{(h_0 - h_1)(h_2 - h_1)}
\]

According to the Derjaguin approximation [1,2] the colloidal force acting along the centre line between particles made of the same material as above flat surfaces and placed in the same medium is equal to

\[
F(h) = \pi a \int_{h_0}^{h} \Pi(h) dh,
\]  

(26)

The interaction energy is:

\[
U(h) = \int_{h_0}^{h} F(h) dh
\]  

(27)

The interaction energy calculated for three sets of parameters used in this study is presented in Fig. 1, which shows clearly that the adopted approximation represents the main features of the real interaction energy: the presence of both repulsion and attraction as well as the presence of a potential well. Changing parameters allows changing not only the depth of potential well but also the shape of potential curve – the range of colloidal forces and co-ordinate, where the energy has a minimum. Actually, if a precise potential curve, based, for example, on Eqs. (2)–(9) and accounting for the retardation effect is known then it can be fitted by using the accepted model with a reasonable accuracy.

It has been assumed that the density difference between particles and dispersion medium is negligible, and therefore pure perikinetic aggregation is considered. It was also assumed the presence of strong repulsion barrier preventing the coagulation in the deep primary minimum.

Eq (14) was solved for the particles with radius 1 \( \mu \)m by the finite difference Euler’s method taking into account the interaction of a particle with nearest neighbours. Periodic boundary conditions were imposed on the whole system to simulate the behaviour of an unbounded colloidal suspension. A uniform initial distribution of particles over the 2-D lattice was used. The set of Langevin equation with the inertial term included was used in simulations. In this case the average velocity of particle corresponds to its energy of thermal motion [69,70] and in this way is an important control parameter assuring that there is no artificial pumping or loss of energy. The initial particles velocities, \( V_o \), were generated according to the Maxwell distribution.
4. Results and discussions

Fig. 2 demonstrates dependency of aggregation kinetics on the depth of potential well. Two parameters have been calculated, which are the average number of particles in the aggregate (Fig. 2a) and the number fraction of singlets (Fig. 2b). It can be seen that the equilibrium establishes very quickly at the small depth of the potential well, which is now 3 kT. As the interaction energy in this case is close to the energy of the thermal motion, the long living clusters are absent at 3 kT and mainly doublets and triplets with the short life time appear as it is seen in Fig. 3a. Only about 50% of particles are included in these temporary small aggregates which are in the dynamic equilibrium with singlets.

By the increase of the depth of potential well the growth rate of aggregates increases and the decrease of singlets occurs more quickly, but time needed to equilibrate the system increases. Aggregates size increases with the increase of the interaction energy, whereas the number of singlets decreases. At $U_{min} = 6$ kT the average number of particles in the aggregate reaches about 3.5, there are already rather large long-living aggregate in dynamic equilibrium with singlets (Fig. 3b). The number fraction of singlets is about 15%. At $U_{min} = 20$ kT one can expect irreversible aggregation in the system and indeed, the singlets practically disappears in this case already after 20 s (Fig. 2b, curve3, Fig. 3c), the mean cluster size increases continuously and most probably in the final state all particles will belong to the one large aggregate.

In Fig. 4 the kinetic curves are presented for the shorter than in Fig. 2 range of colloidal forces and 4 different values of potential well depth. The aggregation at $U_{min} = 4$ kT is very low and more than 50% particles are singlets. It is seen that curves for $U_{min} = 8$ kT and
U_{\text{min}} = 20kT are very close to each other and show practically linear increase of the mean number of particles in the aggregate \( n_c \) with time \( t \). It is in line with the Smoluchovski theory, which predicts

\[

n_c = 1 + k_f n_0 t,
\]

where \( k_f \) is the flocculation rate constant, \( n_0 \) is the initial number concentration of particles. At the same time the shape of aggregates obtained for the case of irreversible aggregation (Fig. 3b) is far from spherical supposed by Smoluchovski. The interval of the interaction energies where the formation of stable clusters in equilibrium with singlets can be expected is between 4 and 8 kT, at least for the chosen range of colloidal forces.

Noteworthy that the results presented in Figs. 2 and 4 are in a good qualitative agreement with the experimental data on formation of equilibrium aggregates, namely on the time dependence of the reciprocal of the number concentration of particles, which characterizes the size of aggregates (Ref. [74], Fig. 1), and time dependence of percentage of singlets in suspension (Ref. [75], Fig. 2).

Surprisingly the range of colloidal forces affects only slightly the aggregation process (Fig. 5). The general trend is, as it could be expected, the decrease of range of colloidal forces slows down the aggregation, decreases the aggregates size and increases the number fraction of singlets. This trend is seen more clearly at larger volume fractions.

The decrease of fraction of solid results in the deceleration of aggregation for all studied parameters of potential well. Remarkably, that even in the case of irreversible aggregation \( (U_{\text{min}} = 20 \text{kT}) \) at fraction of solid 0.19 there still remain about 10% singlets after 30 s of aggregation (Fig. 6). At \( U_{\text{min}} = 6 \text{kT} \) and the same values of \( h_0, h_1 \) and \( h_2 \) as in Fig. 6, by the decrease of fraction of solid from 0.32 to 0.19 the number fraction of singlets increases from about 15% to about 30% and the mean number of particles in aggregate decreases from about 3.5 to 2 after 30 s of aggregation.

The importance of hydrodynamic interactions between particles is clear from Fig. 7. The hydrodynamic resistance to the particles approaches increases greatly as the separation decreases (see Eqs. (18) and (19)). That means that the particles move slower under action of the same force at shorter distances. The hydrodynamic interactions slows down the aggregation processes and, if they are not taken into account, then the time of the system equilibration is underestimated, whereas the mean cluster size is overestimated. This tendency was clearly seen for all studied parameters of potential well and fraction of solid. As the considered here case is two-dimensional, it may be not quite correct to compare the values of flocculation rate.
constant with those obtained from Smoluchovski theory, namely \( k_F = 6.1 \times 10^{-18} \text{ m}^3/\text{s} \) for the case when hydrodynamic interactions and colloid forces are not taken into account [52]. Nevertheless extrapolation of the results presented in Fig. 7a to three-dimensional conditions gives the values \( k_F = 8.2 \times 10^{-18} \text{ m}^3/\text{s} \) for the case when hydrodynamic interactions are not taken into account and \( k_F = 4.9 \times 10^{-18} \text{ m}^3/\text{s} \) when they do. So, the agreement is surprisingly good. The higher in comparison to Smoluchovski theory value for \( k_F \) obtained in numerical simulations in absence of hydrodynamic interactions is obviously the result of acceleration of aggregation due to colloidal attraction. It is also easy to calculate, that the rate constant becomes of about 1.7 times smaller, when hydrodynamic interactions are taken into account. Characteristic flocculation time, i.e. the average time between collisions of particles can be also estimated as about \( t_f = 4 \text{ s} \) in the absence of hydrodynamic interactions and \( t_f = 6 \text{ s} \) with hydrodynamic interactions for fraction of solid 0.32.

Comparison of the characteristic aggregation time with the average lifetime of doublets estimated in [70] enables to make some conclusions about aggregation character. The life time of doublet in potential well of depth \( U_{\text{min}} = 3 \text{ kT} \) is about \( t_d = 0.65 \text{ s} \) what is nearly an order of magnitude smaller than flocculation time. According to [52], if \( t_d < t_f \) then the equilibrium state represents the equilibrium between singlets and doublets with the normalized number concentration of doublets

\[
    n_2 = \frac{t_d}{t_f} (1 - \exp(-t/t_d)).
\]

(29)

The presented above numerical results are in good qualitative agreement with this conclusion. For \( U_{\text{min}} = 3 \text{ kT} \) the time \( t_d \) is essentially lower than, but still comparable with \( t_f = 6 \text{ s} \), that is why not only doublets, but also a small amount of triplets are present in equilibrium state (Fig. 3a). For the system presented in Fig. 2 at equilibrium \( n_1 = 0.52, n_2 = 0.167, n_3 = 0.049 \). The obtained equilibrium value of \( n_2 \) is slightly larger than that calculated according to Eq. (29) \( (n_2 = 0.11) \), as it has been expected.

The life time of doublet in potential well of depth \( U_{\text{min}} = 5 \text{ kT} \) is about \( t_d = 4 \text{ s} \), for \( U_{\text{min}} = 7 \text{ kT} \ t_d = 14 \text{ s} \). Therefore for these cases one can expect reversible aggregation with large aggregates present and \( U_{\text{min}} = 7\text{kT} \) should be close to the limit of irreversible aggregation. This conclusion is also in good agreement with simulation results.

It is noteworthy, that the hydrodynamic resistance in the center-to-center direction, Eq. (18), is much larger than that in the perpendicular direction, Eq. (19). There is already no component of colloidal force in the tangential direction. Therefore, the particles
mobility in the tangential direction is much higher, resulting in the rearrangement of particles inside an aggregate, doing it more compact.

5. Conclusions

The forces acting in colloidal suspensions and affecting their stability and aggregation kinetics are considered. The approximations used for these forces in numerical simulations and the importance of the balanced account for both colloidal forces and hydrodynamic interactions are discussed. The results of numerical simulations of aggregation kinetics are discussed and compared with well known analytical approximations.

The direct numerical simulation of aggregation kinetics was performed using the mathematical model based on the Langevin equations and pairwise interaction between Brownian particles. The study has shown that the most considerable changes in the aggregation kinetics occur at the depth of potential well between 4 and 8 kT. Just in this interval the formation of stable aggregates in the shallow secondary potential well can be expected.

The kinetics of aggregation and the size of equilibrium aggregates depend on the fraction of solid. Kinetics slows down, aggregates become smaller and fraction of singlets increases by the decrease of the fraction of solid. The range of colloidal forces in the studied interval 30–100 nm does not affect essentially the aggregation kinetics, but the general trend is – the decrease of the range of colloidal forces slows down the aggregation, decreases the aggregates size and increases the number fraction of singlets.

The simulations have confirmed the importance of taking into account the hydrodynamic interactions between particles, as neglecting these interactions result in the overestimating of aggregates growth rate.

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References