Micro-Hydrodynamic Interaction Mechanisms in TiO$_2$ Nano-Colloidal Suspensions with Different Particle Size Distributions: The Effects of Electrostatic and Steric Stabilization

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ABSTRACT: Micro-hydrodynamic interaction mechanisms of colloidal particles have important effects on the intrinsic properties and behavior of nano-colloidal suspensions, which in turn affect their different potential applications. Particle stability and size distribution are among the important parameters that influence the micro-hydrodynamic interaction mechanisms. The aim of this research is to investigate, both experimentally and theoretically, the effect of stabilization methods on the micro-hydrodynamic interaction mechanisms in TiO$_2$ nano-colloidal suspensions considering the different particle size distributions. The effect of the two stability methods (electrostatic and steric) on the distribution of particle size are experimentally investigated. The effect of different particle size distributions on the motion and net forces (Brownian, gravitational, lift, and drag) acting on colloidal particles is theoretically estimated based on the correlation formula. The interactions between the particle-fluid molecules and colloidal particles themselves are considered in the calculations. The results show that the stability of colloidal particles has a significant effect on the micro-hydrodynamic interaction mechanisms in nano-colloidal suspensions, where different particle size and size distribution can be obtained. Low particle sedimentation is observed in the case of steric stabilization and with low particle concentration, which enhances the particle diffusion coefficient. The laminar motion of the TiO$_2$ particles can be achieved in the case of high stability nano-colloidal suspension. In this case, the flow of particles occurs in the Stock's regime. The investigation of the micro-hydrodynamic interaction mechanisms in nano-colloidal suspensions in different conditions gives clear information on the possibility of their usage in different applications.

KEYWORDS: Micro-hydrodynamic interaction; nano-colloidal suspensions; electrostatic; steric stabilization; particle size distribution.

INTRODUCTION

Colloidal suspensions are materials that consist of the dispersion of solid particles in base fluids. Generally, colloidal suspensions are two-phase mixtures, the first phase represents the dispersed or immiscible particles and the second phase is a base fluid. The motion of particles and the net force acting on particles in colloidal suspensions refer to the micro-hydrodynamic interactions between particle-particle and particle-fluid. The stability, aggregation, and sedimentation of the colloidal particle are strongly affected by the diffusion and migration of particles in base fluids [1]. Colloidal suspensions may include nano-sized particles, which are well known as nano-colloidal suspensions (NCSs). NCSs are considered to be an effective working media in a wide range of applications because they offer unique properties compared to pure fluids; therefore, understanding micro-hydrodynamic interaction mechanisms in NCSs is quite important. Nanoparticles have different properties than those of bulk materials, one of the features of nanoparticles is the high surface area to volume ratio. In comparison with large-sized particles, nanoparticles have the ability to show quantum behavior because of their small size. Actually, the molecular and macroscopic methods cannot be used in the characterization and the analyzing of hydrodynamic interactions of nanoparticles. The properties (physical, thermal, chemical, optical, etc.) of a molecule are the same as the properties of other molecules for a particular material at the molecular size. At the macroscopic size, the properties of a portion of a material are the same as the properties of other portions for the same material. While in the nano level, the properties of a nanoparticle are different from that for bulk materials. In addition, different properties can be observed between the particles themselves in the nano-sized; e.g., a particle with 10 nanometer size has different properties from another particle with 50 nanometer size for the same material. What does this mean? It allows a new way to control and vary the properties of materials. Actually, it needs to change the size of a particle only rather than its composition when particular properties are required. Therefore, new theories and methods have been arisen

to describe the distinct properties of nanoparticles. There are different factors that affect the properties of nanoparticles and NCSs, particle concentration, size, and size distribution are among the important factors [2].

Although NCSs play a significant role in different fields of applications, nanoparticle stability is strongly affecting their properties and potential usages. Different stabilization methods such as electrostatic and steric stabilizations have been used to achieve long term stability NCSs. Electrostatic stabilization means that the surface of the particles become charged to reinforce the repulsive forces between colloidal particles. While additives or surfactants are used to achieve the stability of colloidal suspensions when the steric stabilization method is used. In both methods, a distribution in the particle size occurs under the effects of the collisions and repulsions between particles. The rate of the particle size distribution and the homogeneity of NCSs depend on the rate of particle stabilization [2]. The stability of colloidal particles plays a significant role in the different mechanisms including the forces and motion of particles in NCSs. The different types, shapes, and sizes of colloidal particles have different stability behavior, also, the effect of the dispersion media should be taken into consideration. In order to clarify the micro-hydrodynamic interaction mechanisms in NCSs, it is necessary to investigate the stability and distribution of particle size and their effects on the motion and overall forces of colloidal nanoparticle in different conditions [3,4].

The motion and forces of colloidal particles have been studied in many researches. The random motion of spherical particles is investigated in different studies, the theory of the transient particulate flow has been used in the investigations [5,6]. Particle stabilization and aggregation behavior of colloidal suspensions were studied, considering the effects of different forces. A numerical simulation based on an approximation was used to account the contributions of colloidal forces and hydrodynamic interactions [7]. Optical microscopy was used to investigate the dynamic correlations between colloidal particles, where the electrostatic reaction between particles was examined. The long-term stability of the particles was observed due to the hydrodynamic reactions by the solvents [8]. It was observed that the interaction of nanoparticles with base fluids molecules had an important effect on the thermophysical properties of colloidal suspensions. An enhancement in thermal behavior was obtained due to the nanolayer around the colloidal particles [9,10]. The effect of the interactions of the particles-fluid molecules on the thermal exchange between colloidal particles and the base fluid was described. The flow regimes for colloidal particles were described, those regimes were used in the characterization of colloidal suspensions [11]. The computational techniques were used to investigate the velocity and dynamic behavior of colloidal particles at different conditions. The hydrodynamic mechanisms were explained using different models of simulations as well as useful software for different applications [12]. To obtain clear information about the aggregation process of colloidal particles, the rate of particle sedimentation and the Brownian diffusion coefficient of NCSs were investigated [13]. Although there are many investigations in regarding with the particle motion and hydrodynamic interaction between particles and base fluids, extensive investigations are required to observe the impacts of the different parameters such as particle stability and size distribution on the micro-hydrodynamic interactions in NCSs.

The objective of the present study is to explain the mechanisms of particle-particle and particle-fluid molecules interactions under different conditions. The different factors such as the degree of particle stability and particle size distribution are included in the investigation to observe their impacts on the mechanisms of the interactions. Therefore, an experimental and theoretical investigation is carried out in this study to provide Integrated and extensive information on the micro-hydrodynamic interaction mechanisms in water-based TiO_2 nanoparticle colloidal suspensions in different conditions. The two stability methods (electrostatic and steric stabilizations) are applied to the nano-colloidal suspensions to observe their impacts on the particle stability and size distribution. The motion and net forces acting on colloidal particles are theoretically estimated based on the experimental results (particle aggregate size and size distribution). The effects of the different parameters such as the different stability methods, particle concentration, and particle size and size distribution are included in the calculations.

EXPERIMENTAL SECTION

Preparation and stability of colloidal suspensions

The dispersion process of nanoparticles in base fluids is the most important step in the preparation of NCSs. In order to obtain NCS with good particle stability, the preparation process should be completed carefully. The TiO_2 nanoparticle with an original particle size 10-25 nm was dispersed in distilled water as a base fluid. Different particle concentrations 0.01, 0.05, and 0.1% v/v are considered in the preparation. Particle size and concentration have considerable effects on the stability and particle size distribution of NCSs; therefore, different particle concentrations have been considered in this study.

Because of the large surface area with respect to the volume of nanoparticles and the attractive forces between them, colloidal nanoparticles may adhere together. Particle collision leads to variation in the size of particles in NCSs, which leads to particle size distribution. Because of the weight, the large size particles cannot stay in the colloidal state which leads to particle sedimentation. Therefore, the stability of nanoparticles is one of the important issues in NCSs research and their applications. To obtain high stability NCSs, the two stability methods (electrostatic and steric stabilizations) have been used in this research. The pH value of the TiO_2 NCSs is adjusted at the value of pH=3 which is far from the isoelectric point of TiO_2 particle, this method represents the electrostatic stabilization of TiO_2 NCSs. While the polyvinylpyrrolidone (PVP) additives is used as a surfactant in the preparation of TiO_2 NCSs, this method reflects the steric method of stabilization.

To apply electrostatic stabilization, the electrical charges at the surface of a particle are strengthened to overcome particle collisions. The zeta potential gives an indication for the electrostatic stabilization of colloidal particles, which is the difference in the potential between the charged layer that surrounding the particle (dispersion medium) and a point in the base fluid out of the interface zone (a layer of base fluid attached to the colloidal particle). In the situation of steric stabilization, surfactants or additives are added to NCSs, which become in contact with particle surface to produce a coating layer to prevent particle collisions. Surfactants behave like barriers on the particle surface, which is the preferable method to modify the stability of NCSs [14]. The principles of the electrostatic and steric stabilizations for colloidal particles are shown in Figure 1.
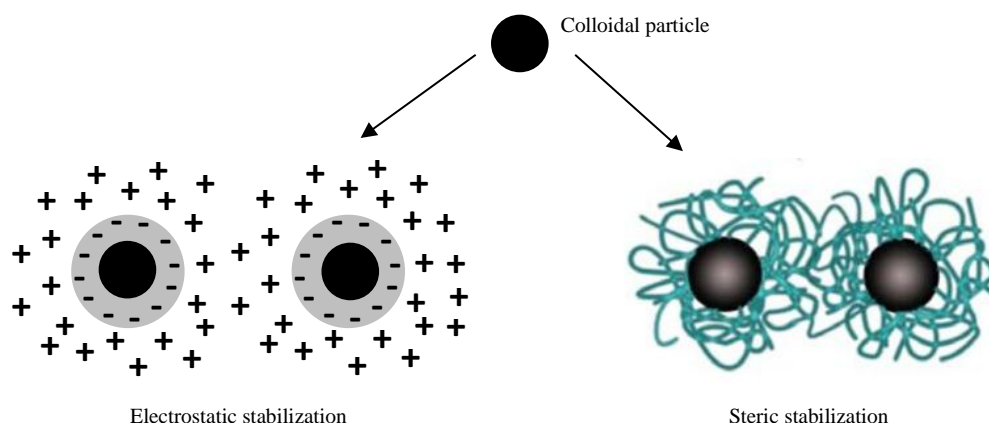

Figure 1: The principles of the two stabilization methods (electrostatic and steric stabilizations) for colloidal particle

Particle size distribution

Particle adhesion in NCSs affects their size and shape, this leads to the formation of different particle aggregates and particle size distribution occurs. On the other hand, the Brownian diffusion and shear force can break down large particle aggregates, which is known as the diffusion or reaction limited particle aggregation. The rate of aggregation of particles is time-dependent; therefore, after a period of time breaking down particle aggregates in NCSs reaches a dynamic balance. In this case, no more changes happen in particle size distribution. The distribution of particle size is an important factor for NCSs because of the small size of nanoparticles and their tendency to produce aggregates. Moreover, the thermal, optical, physical, etc. properties of NCSs are strongly affected by the size distribution of particles.

Most theoretical studies try to explain the process of particle aggregation and particle size distribution in NCSs using different approaches. It is found that a number of limitations can appear in the theoretical models.

Firstly, the prediction of the size of the different particle aggregates and size distributions in NCSs are very complex. Therefore, the theoretical models such as the Brownian-dynamic method is too slow and limited to predict particle aggregation and size distribution for real NCSs systems. Secondly, the optical models require strict conditions and simplifications to predict particle aggregation process. The behavior of radiation scattering from particle aggregates and different particle sizes in a particular NCSs is complex to predict using theoretical models. Experimental techniques are used to monitor particle aggregation and size distribution in NCSs with time. The effects of the different parameters

such as particle size and concentration, pH value, additives, etc. can be evaluated in the experimental investigations [7].

Increasing the concentration of particles can enhance the properties and support the applications of NCSs. However, increasing particle numbers leads to an increase in the rate of particle aggregation and size distribution, which affects particle sedimentation and the stability of NCSs. By overcoming these challenges, it is expected that NCSs can enhance the operation of different systems such as thermal systems. Basically, the stability and the homogeneity of colloidal particles are the main objectives in the applications of NCSs [4].

In this research, the laser diffraction particle size analyzer (LS 13 310) is used to investigate the distribution of particle size in TiO_2 NCSs, as shown in Figure 2. The main particle diameter can be obtained from the data of the particle size distribution. The distribution in particle size is measured by measuring the scattering of the incident radiation by colloidal particles. The scattering radiation is called the scattering patterns or scattering function. The estimation of scattering intensity from different particles in NCSs leads to predict the size of these particles based on the relationship between particle size and scattering intensity [1].

Figure 2. Laser diffraction particle size analyzer
(LS 13 310)

THEORETICAL SECTION

The two-phase or heterogeneous modeling is the most suitable approach for analyzing the motion and slip forces of colloidal particles. In this approach, the liquid phase is treated by using the conventional Eulerian model, while the solid phase (colloidal particles) can be treated either by Eulerian-Lagrangian formulation or by applying a continuous phase (Eulerian-Eulerian model). Observing the Brownian motion and drag force as major hydrodynamic mechanisms can help in predicting the relative velocity of colloidal particles with respect to base fluid molecules.

The Brownian motion is the diffusion of colloidal particles from the region of high to low concentrations. The interaction between colloidal particles under the Brownian diffusion has a significant effect on enhancing the transport properties and thermal performance of NCSs. The particle size and size distribution, particle concentration, and the temperature of NCSs have important impacts on the Brownian diffusion [15]. Considering the effect of the slip mechanisms of colloidal particles, the net force is used to analyze the motion of the particles. In the Lagrangian model, the equation of motion of colloidal particles can be defined as follows [16]:
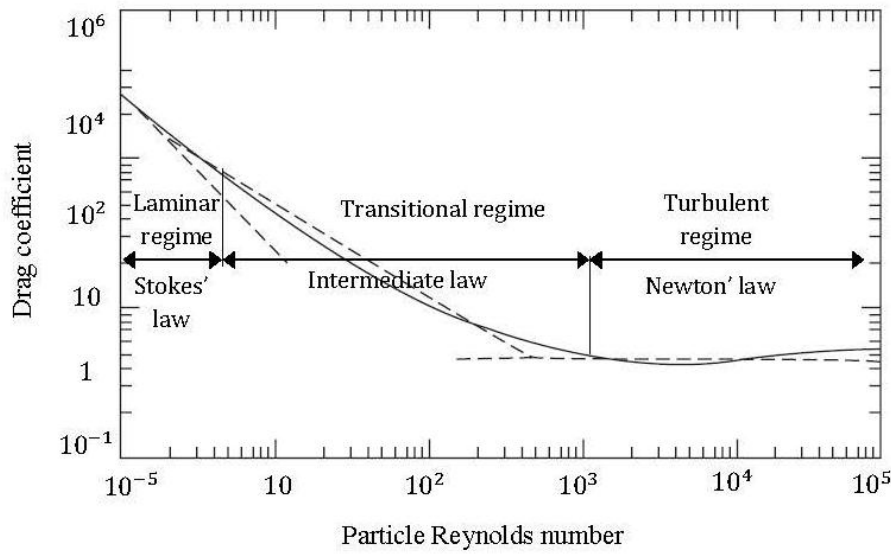
Figure 3. Drag coefficient diagram for colloidal particles [21]

$$m_p \frac{dv_p}{dt} = \sum F \qquad (1)$$

where m_p and v_p are the mass and volume of a colloidal particle; respectively, t is the time, and F is the net force acting on a colloidal particle.

The net force is the sum of all forces acting on a colloidal particle, which can be expressed in an algebraic form as [17]:

$$\sum F = F_G + F_L + F_D + F_B \qquad (2)$$

where the subscripts G, L, D, and B represent the gravity, lift (bouncy), drag, and Brownian, respectively.

Colloidal particles in base fluids can experience both a gravitational and lift (buoyant) forces. These forces act in the vertical direction, the gravity force is directed downward while the buoyant force acts in the upward direction. These forces are expressed as follows [2]:

$$\begin{aligned} F_G &= m_p g \\ F_L &= m_f g \end{aligned} \qquad (3)$$

The mass of a colloidal particle (m_p) is equal to the particle density multiplied by the particle volume ($\rho_p v_p$). While the mass of the displaced fluid (m_f) is equal to the density of the base fluid multiplied by the particle volume ($\rho_f v_p$). The drag force is a result of the difference between the velocities of colloidal particles and base fluid molecules. So, the base fluid exerts a resistive force on colloidal particles. The drag coefficient is a function of the nature of the flow around a colloidal particle and the velocity of a particle. The Reynolds number of a colloidal particle provides an indication of the nature of flow regimes around a particle. The flow regimes can be divided into three regimes, the laminar (Stokes), transition (intermediate), and turbulent (Newtonian) regimes [18]. The drag force on a colloidal particle can be written as flows [18]:

$$F_D = \frac{18\mu}{\rho_p d_p^2 C_c} \qquad (4)$$

Where d_p is the diameter of a particle and C_c is the Cunningham correction factor which is used in the calculation of drag on small (nano-sized) colloidal particles in the case of non-continuum flow. The deviation from the Stock's low assumes no-slip flow condition, which is no longer valid when the ratio of the molecular mean free path to the characteristic length of the colloidal particle is very high. The Cunningham correction factor is given in the form [19]:

$$C_c = 1 + \frac{2\gamma_{mp}}{d_p}(1.257 + 0.4e^{-(1.1d_p/2\gamma_{mp})}) \qquad (5)$$

where γ_{mp} is the nanoparticle mean free path.

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The drag coefficient can be obtained from an empirical model which is given as follows [20]:

$$C_D = \left[0.63 + \left(4.80/\sqrt{Re_p}\right)\right]^2 \qquad (6)$$

Figure 3 explains the relationship between the drag coefficient and particle Reynolds number. The boundaries of the three flow regimes are shown in the figure according to the Reynolds number of colloidal particles [21].

The nanoparticle Reynolds number is given as [18]:

$$Re_p = \frac{\rho_f v_p d_p}{\mu_f} \qquad (7)$$

where vp is the Brownian velocity of a colloidal particle which is estimated from the ratio between particle diameter and the time required to cover this distance of Brownian velocity of a particle [22]:

$$t = d_p^2/6D_B \qquad (8)$$

where D_B is the Brownian diffusion coefficient.
Then the nanoparticle Reynolds number can be as follows [22]:

$$Re_p = \frac{2\rho_f k_B T}{\pi \mu_f^2 d_p} \qquad (9)$$

where $k_B = 1.38 * 10^{-23}(J/K)$ is the Boltzmann constant, T is the temperature of NCSs, and μ_f is the dynamic viscosity of the base fluid.
One of the most important parameters that affect the micro-hydrodynamic interaction mechanisms in NCSs is the particle sediment (settling) velocity. The settling velocity of a particle is given as follows [21]:

$$\begin{aligned}
v_t &= gd_p^2\rho_p/18\mu_f & \text{(Stokes' range)} \\
v_t &= (0.153g^{0.71}d_p^{1.14}\rho_p^{0.71})/(\mu_f^{0.43}\rho_f^{0.29}) & \text{(Intermediate range)} \quad (10) \\
v_t &= 1.74(gd_p/\rho_f)^{0.5} & \text{(Newtons' range)}
\end{aligned}$$

Three forms of particle settling velocity are given in Eq. 10 based on the flow patterns. To desecrate between the particle settling velocity in the three patterns, a dimensionless number K based on empirical correlations is used [23,24]:

$$K = d_p(g\rho_p\rho_f/\mu_f^2)^{1/3} \qquad (11)$$

where $K < 3$ for flow pattern in the Stokes' range, $3 < K < 44$ for flow pattern in the intermediate range, and for flow pattern in the Newtons' range $44 < K < 2350$ [24]. For particles in the nano-sized range, the particle Reynolds number and the dimensionless constant (K) have very low values. Then, colloidal nanoparticles in base fluids are assumed to be in the Stokes' regime of flow [25].
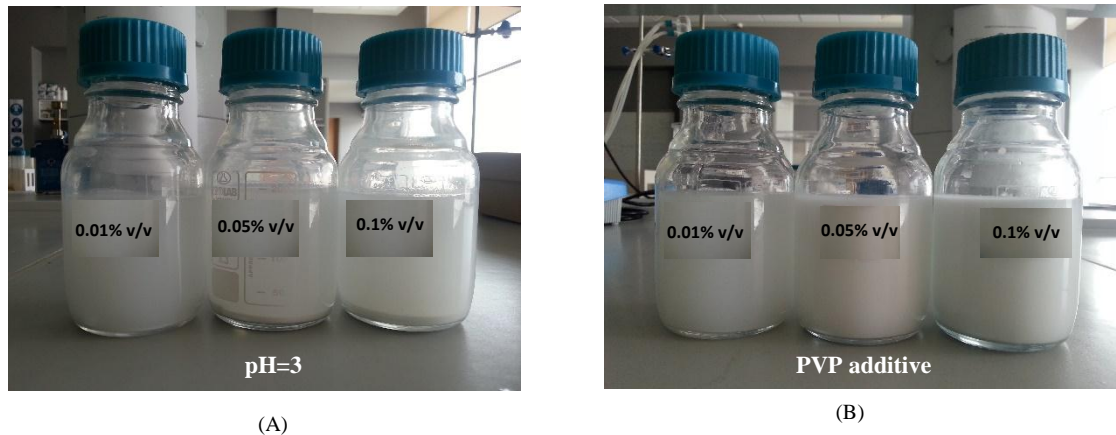

Figure 4. The TiO$_2$ NCSs samples. A) Shows the samples at pH=3, And B) Shows the samples with PVP additives

The effects of the electrostatic and steric stabilizations as well as the particle concentration on the particle size distribution in the TiO$_2$ NCSs are observed by using the laser diffraction particle size analyzer technique. The principles

of light scattering are used in this method where the light intensity patterns are measured to calculate the distribution in particle size based on the relationship between the intensity of scattering of incident radiation and particle size. Therefore, the size distribution of colloidal particles can be obtained by measuring the angular scattering intensity pattern. Figure 5 shows two samples of particle size distribution for TiO_2

The Brownian motion or diffusion is a result of the interaction between colloidal particles and fluid molecules. The temperature and particle concentration are among the important parameters that affect the Brownian motion [26]. The Brownian diffusion becomes an important parameter for nano-sized colloidal particles; more specifically, for particle size less than 500 nm. Indeed, the Brownian motion increases with decreasing particle size. The random motion of colloidal particles is indicated by their diffusion in base fluids, the Brownian diffusion coefficient can be given in the form [25,27]:

$$D_B = \frac{C_c k_B T}{3\pi d_p \mu_f} \qquad (12)$$

RESULTS AND DISCUSSION

The results of this research are divided into two parts. The first part includes experimental results which cover the preparation and characterization of particle size distribution of TiO_2 NCSs. While the second part covers the theoretical results, which demonstrate the micro-hydrodynamic interaction mechanisms in TiO_2 NCSs.

Figure 4 shows the samples of the TiO_2 NCSs in transparent glass containers. The TiO_2 NCSs were prepared using different stability methods. The electrostatic stabilization (pH value adjustment) and steric stabilization (PVP additives) were applied. Different particle concentrations 0.01, 0.05, and 0.1 v/v were used in each type of stabilization methods. Figure 4-A shows the TiO_2 NCSs samples at pH=3, this value of the pH is far from the isoelectric point of TiO_2 particle, which is required for obtaining stable NCSs. Figure 4-B shows the TiO_2 NCSs samples which were prepared using the PVP additives. The steric method is preferable for synthesis a stabile NCSs; on the other hand, the surfactant additives are not suitable in thermal applications because of their chemical behavior at different ranges of temperature. A stability test was performed at certain intervals over the course of two months to observe the stability behavior of the TiO_2 NCSs. It is observed that a large sedimentation rate occurred in the TiO_2 NCSs at pH=3 in comparison with the other types of the TiO_2 NCSs with PVP additives. The TiO_2 nanoparticle remains in dispersion for a long period of time in the case of the steric method of stabilization.

NCSs with particle concentration of 0.01% v/v. The measurements in Figure 5-A shows the particle size distribution for TiO_2 NCSs with PVP additives, and Figure 5-B is for TiO_2 NCSs at pH=3. In Figure 5, the particle size distribution is shown by the particle volume fraction, three readings were recorded for each type of TiO_2 NCSs. The TiO_2 NCSs with PVP additives show a low rate of particle size distribution in comparison with the other types of TiO_2 NCSs at pH=3, which refer to the rate of particle aggregation and the degree of stability of TiO_2 NCSs.
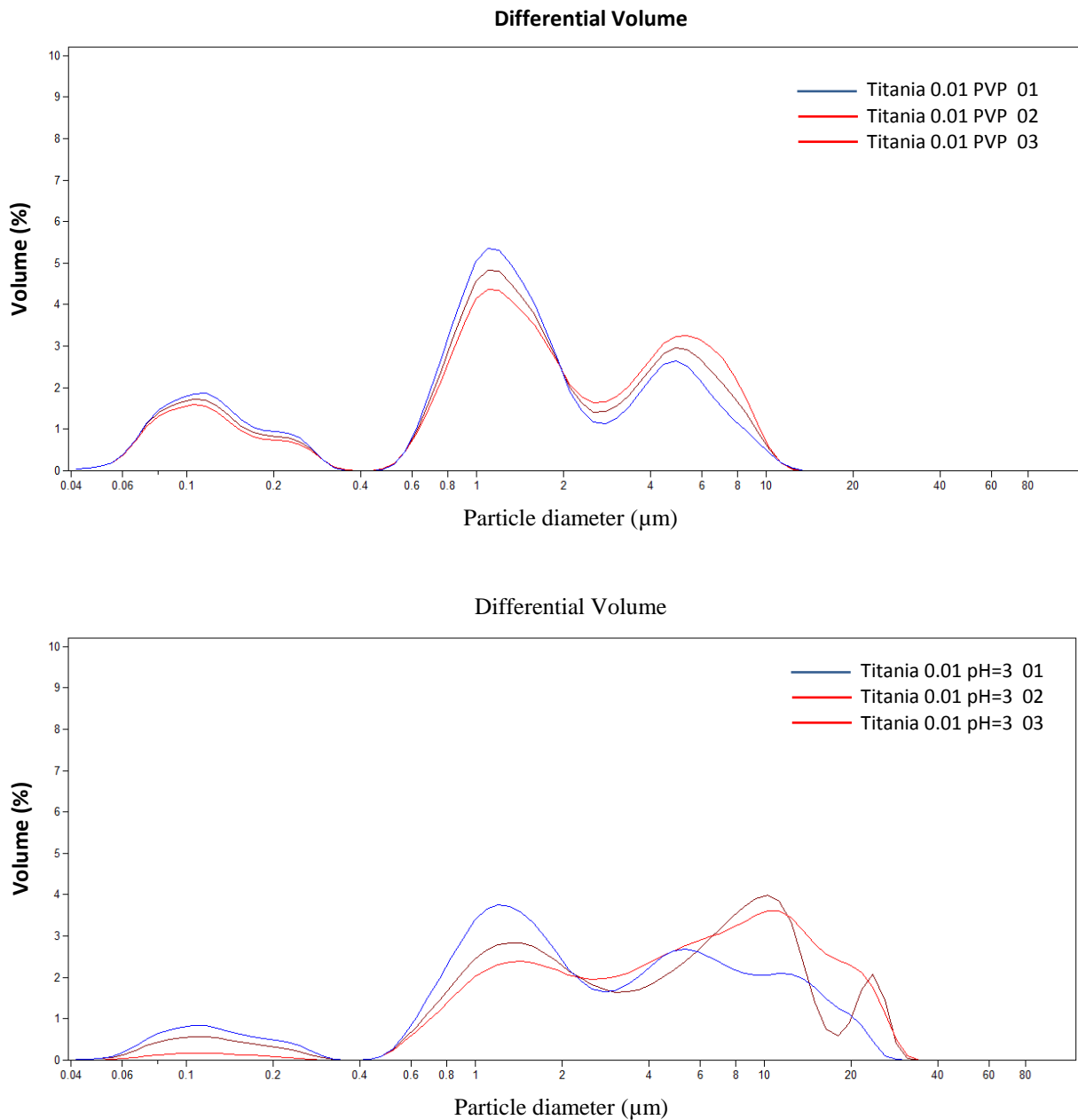
Differential Volume

Figure 5. The particle size distribution for two samples of TiO_2 NCSs with particle concentration of 0.01% v/v. A) TiO_2 NCSs with PVP additives and (B) TiO_2 NCSs at pH=3

The mean particle diameter for each type of TiO_2 NCSs based on the particle size distribution measurements is shown in Table 1. This table explains clearly the effects of the stability method and the particle concentration on the increase in the particle size in TiO_2 NCSs. Increasing the size of particles is a result of particle aggregation in NCSs. The mean particle diameters of TiO_2 NCSs with PVP additives have low values in comparison with other types of TiO_2 NCSs at pH=3 at the same particle concentration. The results in Table 1 reveals the importance of the different stability methods on the particle aggregation process.

Table 1: Mean particle diameter for TiO_2 NCSs

Method of stability	Mean particle diameter (nm)		
	$\emptyset = 0.01\%$	$\emptyset = 0.05\%$	$\emptyset = 0.1\%$
PVP	130	155	200
pH=3	180	304	454

One of the results of increasing particle size is the sedimentation of colloidal particles which is an important parameter in the investigations of the stability behavior of NCSs. The degree of particle aggregation affects the sedimentation rate which is also known as particle settling velocity. Particle settling velocity is directly proportional to particle size due to the gravity effect. Figure 6 shows the particle settling velocity for the TiO$_2$ NCSs. The effect of the two stability methods (electrostatic and steric) on the particle sedimentation rate at different particle concentrations is explained in Figure 6. In addition to the particle size, the density and viscosity of the base fluid affect the sedimentation rate. The effects of the colloidal particle and the base fluid properties are included in the calculations of the particle settling velocity which can be observed in Equation 10. Indeed, decreasing the sedimentation rate of particles as much as possible is one of the requirements and challenges that face their usage in different NCSs applications.
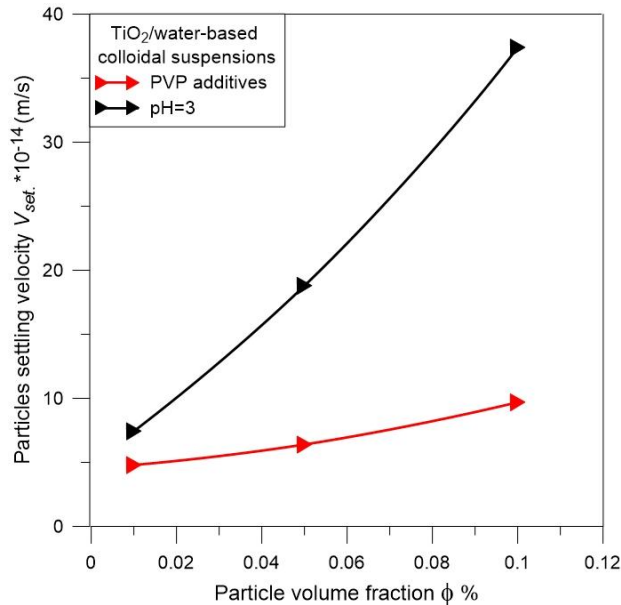

Figure 6. Particle settling velocity for the TiO$_2$ NCSs at the two stability methods (electrostatic and steric

The relationship between the particle size and the Reynolds number is explained in Figure 7. The effects of the different parameters (stability and particle concentration) are shown. The mean particle diameter of TiO$_2$ nanoparticles which is obtained from the distribution of particle size is used in the calculations. The Reynolds number of nanoparticles is inversely proportional to the particle size. The low values of the particles Reynolds number refer to the Stokes flow or so-called as the creeping flow around the nanoparticles. This occurs in the case of ultra-fine particle size, where the effect of the inertia is neglected, and the viscose force dominates. The particle Reynolds number gives an indication on the particle inertial migration in base fluids. When the value of the particle Reynolds number is very low (less than 1), the inertial migration of particles does not occur. While colloidal particles have a different tendency due to the inertia force in the case of large particle Reynolds number (larger than 1).

Figure 8 explains the relationship between the particle Reynolds number and the drag coefficient for TiO$_2$ nanoparticles. The drag force on a particle is a result of the difference in the velocities of colloidal particles and fluid molecules, which is so-called particle-fluid interaction drag force. Physically, the induced drag force is equal to the momentum transferred by a colloidal particle to the surrounding per unit time, a part of the colloidal particle velocity is transferred to the surrounding fluid by momentum. In Figure 8, it can be observed that the drag force on a colloidal particle decreases with decreasing the size of the particle. And it is inversely proportional to the particle Reynolds number. The results of the drag coefficient in this paper are compared with other results for various particles for several values of the viscosity ratio from previous studies [21,28,29]. A good agreement is found between these results. In the condition of Stoke's flow, there is a symmetry in the fore-and-aft fields of the flow around a colloidal particle. At finite particle Reynolds number, the advective effects are very strong, and this symmetry breaks down. It is observed that even at low particle Reynolds number, a wake is formed behind the particle. The wake becomes stronger as the particle Reynolds number increases, and the inertia of the flow around the particle overcomes the viscosity effects on the surface of the particle.
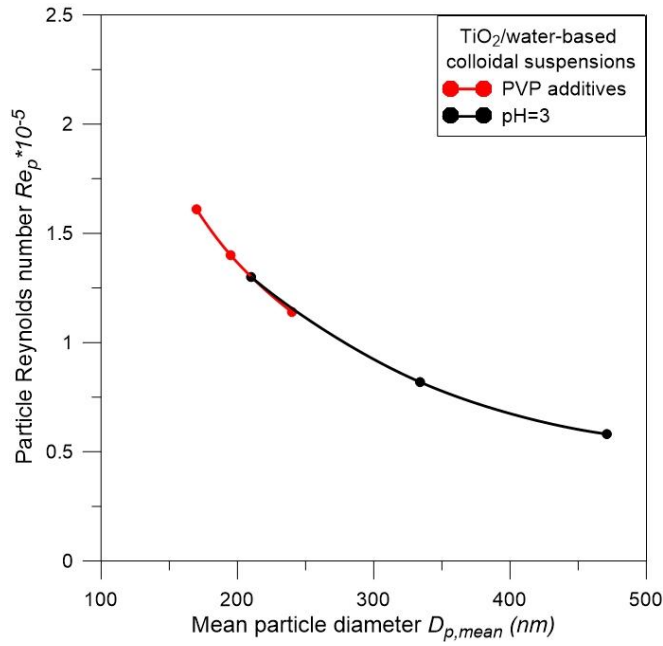
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Figure 7. Particle Reynolds number versus mean paticle diameter for the TiO_2 NCSs at the two stability methods (electrostatic and steric
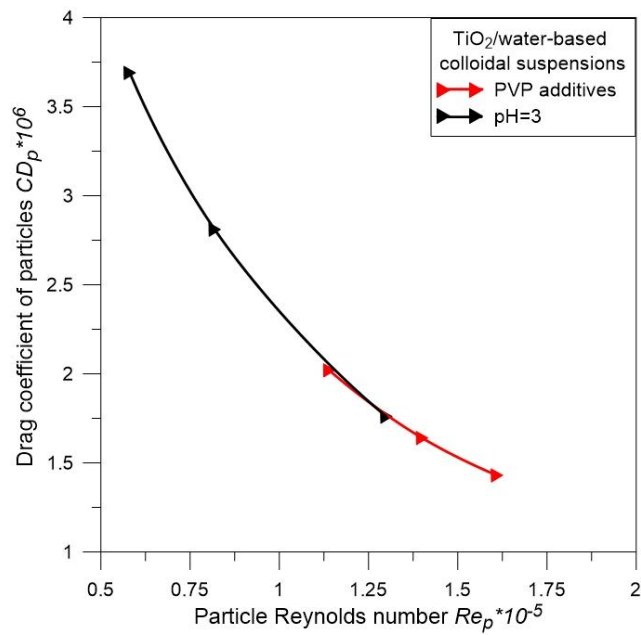

Figure 8. Drag coefficient curve for the TiO_2 NCSs at the two stability methods (electrostatic and steric stabilization)

Figure 9 shows the effect of the colloidal particle diameter on the Brownian diffusion coefficient of the TiO_2 NCSs. The impacts of the two stability methods and particle concentration are shown in this figure. Adhesion and repulsive

interactions are the dominant forces acting at the Brownian diffusion coefficient at the nanoscale. These forces affect the size of the colloidal particles. The results show that the Brownian diffusion coefficient is inversely proportional to the colloidal particle size. The Brownian motion is a result of the impacts of the base fluid molecules on the surface of colloidal particles. Therefore, the interaction between particle-particle and particle-fluid molecules have significant effects on the diffusion coefficient. Enhancing the Brownian motion of colloidal particles leads to modify the dynamics and properties such as the thermophysical properties of NCSs. The rate of the Brownian motion affected by different factors that influence the movement of colloidal particles. For example, decreasing the particle size, increasing the number of particles, and the low viscosity of NCSs increase the rate of Brownian motion. However, it is observed in this study that increasing the particle concentration leads to modify the particle size distribution under different stability methods, which leads an increase in the size of colloidal particles and decreasing the Brownian motion. Therefore, as much as the stability of NCSs and the low particle size distribution can be achieved, the Brownian motion and the micro-hydrodynamic mechanisms in NCSs can be modified.
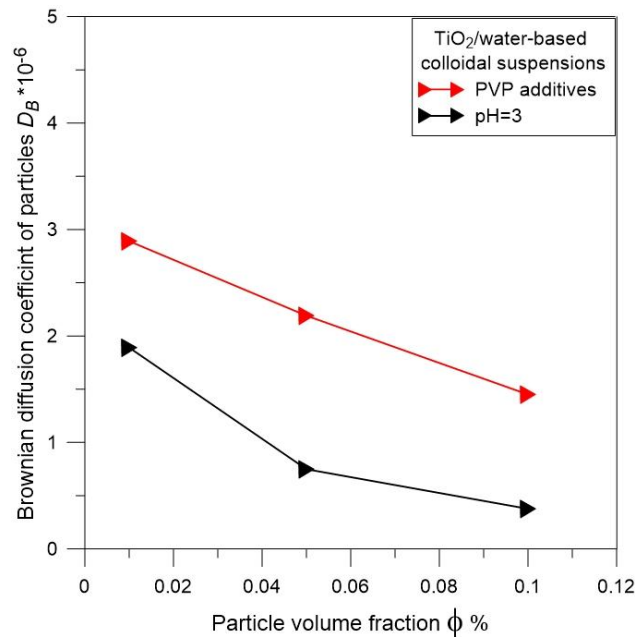

Figure 9. Brownian diffusion coefficient of colloidal particles for the TiO$_2$ NCSs at the two stability methods (electrostatic and steric stabilization)

CONCLUSIONS

This study explains the effects of particle size and size distribution on the micro-hydrodynamic mechanisms in NCSs. Particle stability is significantly affecting the motion and net forces acting on colloidal particles. The relationship between the colloidal particle drag coefficient and Reynolds number carries important indications on the dynamic behavior of colloidal particles. The drag force arises when suspended particle moves or diffuses in base fluids. Important factors that affect the settling velocity (terminal velocity) of suspended particles are explained. Nanoparticles settling becomes a very important issue in the case of the high particle aggregation rate, where the particle size distribution has a significant value. The Brownian motion of colloidal particle is strongly influenced by particle stability, where different particle sizes are obtained using different stability methods (electrostatic and steric stabilizations) and particle concentrations.

Micro-hydrodynamic mechanisms in NCSs play a significant role in the energy transfer between colloidal particles and colloidal particle-fluid molecules. Energy transport in NCSs can be enhanced by the Brownian motion of colloidal particles, where the interaction between particles increases with increasing particle diffusion. In addition, the micro-hydrodynamic mechanisms can provide accurate explanations of the thermal performance of NCSs. Actually, understanding the energy transport and thermal performance in NCSs can help to develop an energy-efficient NCSs for wide and different types of applications.

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