3D numerical study of induced-charge electrokinetic motion of heterogeneous particle in a microchannel

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1. Introduction

Electrokinetic phenomena are based on the interaction of the applied electric field with the electric double layer (EDL) on a solid surface in contact with an aqueous electrolyte solution. Electroosmosis and electrophoresis are the most typical electrokinetic phenomena. A fundamental assumption for “classical” electrokinetics is the linear response of the electrokinetic motion with respect to the applied electric field and the fixed static surface charge on non-conducting solid surfaces. One of the consequences of such an assumption is as follows: Suspending particles with fixed and uniform zeta potential in free solutions cannot be separated by their sizes or shapes. Electrokinetics has entered the microfluidics area over the past 10–15 years [1–3]. The primary applications of electrokinetics in microfluidics include electroosmotic pumping, enhanced flow mixing, molecule separation and particle manipulation [4,5]. Microfluidics in turn also enables the new development of electrokinetics. For example, research of electrowetting lead to digital microfluidics [6,7]; studies of dielectrophoresis result in many novel methods of manipulating and separating particles and cells in lab-on-chip devices [8–11].

One of the new branches of the electrokinetics research is called “induced-charge electrokinetics” (ICEK) [12,13]. The pioneering work on electrokinetic flow around polarizable particles was done by Levich in 1962 [14]. Following that, there were a number of studies [15–19] on the behaviour of polarizable colloids in electric field. Experimental observations of this induced charge flow were reported by Gamayunov et al. [20]. They were the first group that predicted the quadrupolar-induced charge electro-osmotic flow around an ideally polarizable sphere in a uniform electric field, and the resulting relative motion of two spheres. Later on, Ramos et al. [21] discovered alternating-current electro-osmotic flow (AC-EOF) over microelectrodes. This idea was proposed to be used as low voltage microfluidic pumping method by Ajdari [22] one year later. The experimental results produced by Green et al. [23,24], Gonzalez et al. [25], Brown et al. [26], and Studer et al. [27] focused on non-linear AC electrokinetics in microfluidics [28,29] and confirmed the findings of the Ramos et al. [21] and Ajdari [22]. In 2004, Bazant and Squires [12,13] used the term “induced-charge” flows to describe the physical mechanism of applied electric field acting on its induced charge near a polarizable surface. They also noted that the effect described earlier in the Russian literature on metallic colloids by Murtsovkin [30] and Gamayunov et al. [31] is essentially the same. Few years later, Wu et al. [32–35] reported complete 3D transient numerical studies of induced charge electrokinetic flow phenomena associated with ideally polarizable surfaces and ideally polarisable particles in microchannels.

So far there has been no reported study of induced charge electrokinetic phenomena for heterogeneous polarisable particles. The heterogeneous polarisable particles here will be referred as “Janus particles”. The name “Janus” is from the Roman God who has two faces looking into opposite directions. In this study, the Janus parti-
cle is a sphere, a half of it is metal (the polarisable half) and another half is polymer (the non-polarizable half). This paper presents the first 3D transient numerical model and simulations of the phenomena associated with the flow field and the motion of such a Janus particle in a microchannel under applied electric field. In this study, we begin with basic cases to show the differences between “classical” EK, ICEK, and combination of those cases by 3D numerical simulation of the behaviour of a non-polarizable particle, a fully polarizable particle and a Janus particle in a microchannel, respectively. Knowing the dependence of the flow field and the particle’s motion on the polarizability and the polarisable-nonpolarizable heterogeneity, we then studied the induced-zeta potential on the Janus particle surface, and its effect on slip velocity on the particle surface. Furthermore, the dependence of Janus particle motion on the size of particle, external applied electric field, orientation of Janus particle relative to the applied electric field and the size of the polarisable portion are also examined in this study.

It should be noted that when the gap between the particle and the channel wall is small, other effects such as dielectrophoresis may become significant. However, we did not consider these effects in this study for the following considerations. First, in this study, the particle size is 20 μm, the channel size is 40 μm. The gap size is 10 μm, not very small. It can be shown that the dielectrophoresis effect in this case is not significant. The dominant interaction between the particle and the channel wall is the vortices of the induced charge electrokinetic flow. Secondly, the current study is the first investigation of the translational motion of Janus particle in full 3D numerical simulation. At this point, we want to highlight the main phenomena associated with a polarizable particle and the induced charge electrokinetics. Therefore, we neglect the other phenomena that might distract the attentions of readers from the main goal of this study.

2. Theory of ICEK

Consider an ideally polarizable object with arbitrary geometry which is immersed in an aqueous solution (Fig. 1). Suddenly an external electric field \( \vec{E}_e \) is applied to the system. Immediately, an electric current, \( J = \alpha \vec{E}_e \), generated in the aqueous solution enters the polarizable particle. The electric field lines intersect the polarizable particle at the right angles initially (Fig. 1a). Originally, the positive and negative charges in the polarizable particle were randomly distributed so that particle was electrically neutral initially. These charges are affected by the current. The current drives the negative charges into a thin layer on one side of the polarizable particle and the positive charges to the other side, inducing equal and opposite surface charge, \( q \), on the polarizable particle surface. In turn, the surface charges attract the counter-ions in the liquid. As a result of this charge rearrangement, a dipolar screening cloud adjacent to the solid-liquid surface forms. This new pattern of charge and ion orientation does not let the current goes through the polarizable particle. The particle and the dipolar screening cloud act like an insulator particle to the applied electric field. An induced dipolar double layer is formed (Fig. 1b) and a steady-state electric field is established. The above mentioned process happens very quickly (on the order of \( 10^{-4} \text{ s} \)), thus the transient charging process is usually negligible in comparison with the characteristic time of most microfluidics transport processes.

Evaluating the zeta potential of the induced charge is critical to calculate the velocity of the induced-charge electrokinetic motion of the liquid near the particle surface and the particle itself. For relatively simple and regular geometries, there exists analytical expression of the induced zeta potential. For instance, Bazant and Squires have derived an analytical formulation of the induced zeta potential on the surface of a 2D circular cylinder given by

\[
\zeta (\theta) = 2E_0 a \cos \theta
\]

where \( \theta \) is angular coordinate and \( a \) is the radius of the cylinder. This equation indicates that the induced steady-state zeta potential \( \zeta \) is proportional to the local electric strength \( E_0 \) and varies with position on the conducting surface. However, for a surface of a complex or irregular shape, there is no simple analytical solution for the distribution of the induced zeta potential. Thus, a numerical scheme is needed to relate the induced zeta potential with the external applied field. In 2008, Wu and Li [32–35], proposed a method which could numerically determined the steady-state induced zeta potential distribution, \( \zeta_i \), on an ideally polarizable particle surface.

The induced screening cloud generates a local electric field and acts as an insulating shell over the conducting surface so that the field lines of the externally applied electric field cannot intersect the surface. Thus, the local strength of the induced field \( \vec{E}_i \) on the conducting surface, i.e., the local potential gradient along the surface, should be of the same magnitude as that of the externally applied electric field \( \vec{E}_e \), i.e.,

\[
|\vec{E}_i| = |\vec{E}_e|
\]

Because the image charges in the conductor have an opposite sign to that of the ions attracted at the conducting surface from the liquid, the induced electric field at the conductor–liquid interface should be in the opposite direction to that of the external field that is

\[
\vec{E}_i = -\vec{E}_e
\]
\[ \nabla \zeta = -\nabla \phi_e \]  

where \( \phi_e \) is the local externally-applied electric potential given by

\[ \nabla^2 \phi_e = 0 \]  

Assuming that the conductor is initially uncharged, the integration of the induced charge over the whole conducting surface should be zero because of the initial electric neutrality of the surface. Thus, the integration of the induced zeta potential over the conducting surface should be zero, that is

\[ \int_S \zeta_i dS = 0 \]  

where \( S \) is the conducting surface in the applied electric field. If the conducting surface is initially charged, the final steady-state zeta potential distribution may be a superposition of the initial equilibrium zeta potential \( \zeta_0 = \zeta(t = 0) \) and the induced zeta potential \( \zeta_i \).

If we limit our attention to the case of thin double layer and small Dukhin number (i.e., surface conduction is negligible compared to the bulk conduction), and no electrochemical reactions are present at the conductor–liquid interface, the above conditions are valid. The following method can be used to numerically calculate the induced zeta potential distribution on the conducting surfaces from the known external electric potential \( \phi_e \). Directly integrating Eq. (4), the local induced zeta potential is obtained as

\[ \zeta_i = -\phi_e + \phi_c \]  

where \( \phi_c \) is a constant correction potential. By inserting Eq. (6) into Eq. (5), we can evaluate the correction potential as

\[ \phi_c = \frac{\int_S \phi_e dA}{A} \]  

where \( A \) is the area of the entire surface of the conducting object. Eqs. (6) and (7) provide a quick and simple numerical method to calculate the final steady state induced zeta potential distribution on the conducting surfaces with arbitrary geometries.

In this paper we follow the strategy described above to calculate the induced zeta potential on the polarisable portion of the Janus particle. The externally applied electric field generates a body force on the ions in the induced dipolar double layer. This force drives the ions and the liquid into motion (i.e., the electroosmosis). This electroosmotic flow will be modeled as the slip flow on the particle surface. In case of Janus particle, the slip velocity on the non-polarizable part of Janus particle may be in a different direction as that of the polarizable part. As a result of these variations, different vortices in opposite directions generate near the solid–liquid interface (see Fig. 2).

3. Three dimensional governing equations of transient ICEK motion of Janus particle

As discussed earlier, the polarizable section of Janus particle will be polarized by the externally applied electric field and a multipolar induced electric double layer adjacent to the solid–liquid interface will be formed, as shown in Fig. 2. The induced steady-state zeta potential on the particle surface \( \zeta_P \), given by Eq. (2), varies with position on the conducting surface, resulting in micro vortices near the particle surface. The interaction of the applied electric field with the induced surface charge on the conducting part of the particle and the electrostatic charge on the non-conducting part of the particle will create the electrophoretic motion of the particle. The electrostatic charges on the non-conducting microchannel walls will also cause EOF in the channel under the same applied electric field. The net velocity of the particle will be determined by the electrophoretic motion of the particle, the bulk liquid EOF and the complex flow field (vortices) around the particle. A complete 3D transient mathematical model is set up to simulate the electric field, the flow field and the particle motion in the system, as described in the following sections.

In this paper, for simplicity, we considered only the translational motion of Janus particle in a microchannel. Our other studies indicate that the Janus particle tents to rotate only if it is not aligned with the electric field direction. The rotation will complete very quickly so that the Janus particle will be aligned with the applied electric field. In other words, for most of time or in the steady state, a Janus particle will have only the translational motion in a straight microchannel under a constant DC field.

3.1. Electric field

Once the polarizable section of the Janus particle is polarized and a steady state induced double layer is setup on the conducting surface, the applied electrical potential in the liquid \( \phi_e \) is governed by the Laplace’s equation (Eq. (4)) and the corresponding boundary conditions

\[ n \cdot \nabla \phi = 0 \quad \text{at channel wall and particle surface} \]  

\[ \phi = \phi_0 \quad \text{at channel inlet} \]  

\[ \phi = 0 \quad \text{at channel outlet} \]  

3.2. Flow field

The equations governing incompressible liquid flow in the microchannel are the Navier–Stokes equation and the continuity
equation.

\[
\rho \left( \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u}
\]

(10)

\[\nabla \cdot \vec{u} = 0\]

(11)

with the boundary conditions [37]

\[
\vec{u} = -\frac{\varepsilon_0 \varepsilon_w \vec{E}}{\mu} \quad \text{at channel wall}
\]

(12a)

\[
\vec{u} = \vec{V}_p - \frac{\varepsilon_0 \varepsilon_w \zeta_p \vec{E}}{\mu} \quad \text{at particle surface}
\]

(12b)

\[
\hat{n} \cdot \nabla \vec{u} = 0 \quad \text{at inlet and outlet}
\]

(12c)

where \(\zeta_w\) is the zeta potential on the channel wall, \(\vec{E} = -\nabla \phi_e\) is the local applied electric field, \(\vec{V}_p\) is the translational velocity of the particle, and \(\zeta_p\) is the zeta potential on the particle surface (i.e., it is the induced zeta potential on the conducting part, and the electrostatic charge caused zeta potential on the non-conducting part). Here, the transient term in Eq. (10), \(\vec{u}\) cannot be dropped off because the system is physically time-dependent. The particle considered in the system has a fairly big size (20–30 \(\mu\)m) which is comparable with the channel size (100–300 \(\mu\)m). The bulk liquid flow influences the particle’s motion and the particle’s motion will also affect the flow field. Thus the model presented here describes a fully coupled transient particle–fluid interaction.

3.3. Particle motion

Since the particle carries induced surface charge, there is electrostatic force acting on the particle by the applied electric field. At the same time, the flow field exerts a hydrodynamic force on the particle. The net force acting on the particle is [37]

\[
\vec{F}_{net} = \vec{F}_E + \vec{F}_h
\]

(13)

where \(\vec{F}_E\) is electrostatic force and \(\vec{F}_h\) is total hydrodynamic force, which combines two components

\[
\vec{F}_h = \vec{F}_{ho} + \vec{F}_{hin}
\]

(14)

where \(\vec{F}_{ho}\) is the hydrodynamic force acting on the particle by the liquid flow in the region outside the EDL, and \(\vec{F}_{hin}\) is the hydrodynamic force acting on the particle by the liquid flow in the region inside the EDL.

In the model presented here, the electrical double layers are assumed so thin that the Debye length can be neglected in comparison with the size of the particle (20–30 \(\mu\)m) and the size of the channel (100–300 \(\mu\)m). Thus, detailed flow field in the region inside the EDL will not be considered, and the effect of flow field in the EDL is replaced by the electrosomotic velocity which acts as a slipping flow boundary condition for the flow field in the region just outside the EDL. In this way the flow field around the particles is the flow field originated outside the EDL and subject to the slipping flow boundary condition at the particle surface. Under this assumption, it can be shown that the \(\vec{F}_E\) is balanced by \(\vec{F}_{hin}\), and the net force on the particle is thus given by [37]

\[
\vec{F}_{net} = \vec{F}_{ho} = \vec{G} - \int \sigma_p \cdot \vec{n} dS = (\rho - \rho_p) g \vec{V}_p - \int \sigma_p \cdot \vec{n} dS
\]

(15)

where \(\vec{G}\) is the total body force, \(\rho_p\) is the density of the particle, \(\sigma_p\) is the volume of the particle, \(g\) is acceleration due to gravity and \(\sigma_p\) is the stress tensor given by

\[
\sigma_p = -\bar{P} + \mu \left( \nabla \vec{u} + (\nabla \vec{u})^T \right)
\]

(16)

where \(\bar{P}\) is identity tensor.

The particle motion is governed by

\[
\vec{F}_{net} = \vec{F}_E + \vec{F}_h
\]

(17)

According to Eq. (15):

\[
\frac{d\vec{V}_p}{dt} = \vec{F}_{net} = (\rho - \rho_p) g \vec{V}_p - \int \sigma_p \cdot \vec{n} dS
\]

(18)

Substituting Eq. (16) in Eq. (18)

\[
\frac{d\vec{V}_p}{dt} = (\rho - \rho_p) g \vec{V}_p - \int \left\{ -\bar{P} + \mu \left( \nabla \vec{u} + (\nabla \vec{u})^T \right) \right\} \cdot \vec{n} dS
\]

(19)

where \(m_p\) is the mass of inertia of the particle. The displacement of the particle center is governed by

\[
\frac{d\vec{X}_p}{dt} = \vec{V}_p
\]

(20)

The initial conditions of the particle motion and the flow velocity are set as zero, that is

\[
\vec{V}_{p,l=0} = 0, \quad \vec{u}_{l=0} = 0
\]

(21)

In the development of the numerical simulation, the following non-dimensionalized parameters are used:

\[
\vec{\phi}_w = \frac{\phi_e}{\zeta_w}, \quad \vec{u} = \frac{\vec{u}}{U_{ref}}, \quad \vec{P} = \frac{p - \rho U_{ref}^2}{\rho U_{ref}^2}, \quad {\bar{E}} = \frac{E}{\zeta_w L}, \quad {\bar{x}} = \frac{x}{L}, \quad {\bar{t}} = \frac{t}{U_{ref}}
\]

(22)

where \(U_{ref} = \frac{\varepsilon_0 \varepsilon_w}{\varepsilon_0 \varepsilon_w} \times \frac{\varepsilon_0}{\varepsilon_w}\) is the reference velocity. In order to non-dimensional lifting force we can use the following relation

\[
\vec{F}_{net} = \frac{F_{net} \cdot \mu^2}{\rho (\varepsilon_0 \varepsilon_w)^2}
\]

(23)

4. Numerical simulation and the computational domain

The ICEK motion of a spherical Janus particle placed at the centerline of a straight microchannel is investigated. The microchannel length is 15 \(\times\) \(D\) and its width and height are 2 \(\times\) \(D\). The particle is a sphere with a diameter of \(D\) made of a half of a fully polarizable material and a half of a non-polarizable material. The particle is initially placed at the point (3 \(\times\) \(D\), 1.5 \(\times\) \(D\), 1.5 \(\times\) \(D\)) at the center of the channel (see Fig. 3b). The non-dimensionalized applied electric field strength through the microchannel is set as \(\bar{E} = E/(\zeta_w L) = 200\). The channel walls and also the non-polarizable surface of Janus particle carry uniform negative electric charges that are characterized by the zeta potentials. The zeta potentials on the particle surface and on the channel walls are \(-60\) mV and \(-15\) mV, respectively. The density of the particle is considered the same as the liquid in order to avoid the gravity effect. Clearly, the system is symmetrical to the \(x\)- and \(y\)-planes. The two walls which are parallel to the \(x\)-plane are defined as the inlet (left hand side) and outlet (right hand side). The ends of the channel are connected to open reservoirs, so that no overall pressure gradient is present in the system. The computational domain is fully covered by three-dimensional tetra meshes. The prepared domain is solved by commercial software FLUENT 12 which was in correlation with visual C to run the UDF file that was written for solving the moving mesh and particle motion in three-dimension. A moving grid technique is utilized to fulfill the numerical simulation of the particle–liquid coupled multi-physics system under various conditions. The corresponding effects of micro vortex generation and particle–wall interaction are discussed. A non-uniform spaced grid was employed for more
5. Results and discussion

In order to numerically investigate the fundamental behaviour of induced-charge electrokinetic phenomena around a Janus spherical particle in a microchannel, we implement the above mentioned governing equations and proper boundary conditions to the system. Nevertheless, as mentioned before, we considered only the translational motion of a Janus particle in a straight microchannel in the current investigation for simplicity. The Janus particle potentially tents to have a translational movement as long as it is aligned with the electric field direction. If by any reason there is an angle between Janus particle interface and the external electric field direction, the Janus particle will rotate to reduce this angle. Such a rotation will be completed very quickly so that the Janus particle is aligned with the applied electric field. In other words, for most of the times or in the steady state, a Janus particle will have only the translational motion in a straight microchannel under a constant DC field.

Gangwal et al. [38] in 2008 experimentally showed that a Janus particle under AC electric field will move perpendicular to the direction of external electric field. However, their situation is very different from the model system in our study, because (i) their electric field is not uniform as shown in the Fig. 1b of their paper, and (ii) they used AC field, and the AC induced charge EK may produce a different force. In our study, we consider the steady state motion of a Janus particle in a straight microchannel under a constant DC field. The particle will move in the axial direction only.

### 5.1. Three dimensional micro-vortex generation and particle motion

It is well known that a suspended micro-particle (either non-polarizable or polarizable) in a microchannel under the applied electric field will move. However, to understand what will happened when the polarizability of a particle changes, first, we conducted numerical simulations for three different cases, (i) a non-polarizable particle, (ii) a polarizable particle, and (iii) a Janus particle. All those cases are considered at the same initial condi-
tions and boundary conditions such as the external applied electric field, geometry, initial position. The results are plotted in Fig. 4. Fig. 4a shows the flow field during the electrophoretic motion of a spherical non-polarizable particle. Since the zeta potential is constant and uniform at any point of the spherical surface of non-polarizable particle, the streamlines smoothly follow the surface of non-polarizable particle and pass it without distortion. However, in the case of a fully polarizable particle, four vortices are generated around the particle as soon as the external electric field applies, as seen in Fig. 4b. As explained earlier once the dipolar induced double layer formed, the externally applied field exerts a body force on the ions in the screening cloud in the liquid. This force moves the liquid, but, because the sign of the surface charge and hence the excess counter ions in the induced EDL changes from the front half to the rear half of the sphere, the direction of liquid flow varies and become opposite to each half. Consequently four vortices around the polarizable particle are generated (Fig. 4b). Similarly, in the case of a Janus particle, there are four vortices on the polarizable side, as shown in Fig. 4c.

In the case of a Janus particle, the polarizable section is a hemisphere which has an induced bipolar EDL, a large portion of positive charge and a small portion of negative charge in the induced EDL, as illustrated in Fig. 2. This bipolar EDL is responsible for the two vortices on the polarizable side. Also seen from Fig. 2, the net charge in the EDL of the non-polarizable part has the opposite sign to the net charge in the EDL on the polarizable part. This difference causes two other vortices on the non-polarizable part. However, due to the much weaker EDL field of the non-polarizable part, these vortices are also much weaker.

The above shows a complete change or a portion change of the polarizable material on a particle will deform the streamlines of electrokinetic flow around the particle, and produce vortices with opposite rotation (see Fig. 4). Now the important question is how those vortices affect the particle motion? In order to answer this question, we simulated the motion of the same three cases as in Fig. 4 for several seconds. Fig. 5 reveals the movement of these three cases for 5 s. Comparing the three cases in Fig. 5, we can see that the net effect of the four vortices around the fully polarizable particle is the reduction of the particle motion, in comparison with the elec-

![Fig. 4. Electrokinetic flow field around a suspended spherical particle in a microchannel. (a) Classical EK flow around non-polarizable particle with a uniform zeta potential of $-60$ mV on the particle surface. (b) Induced-charge electrokinetic flow around a fully polarizable spherical particle. (c) Induced-charge and classical electrokinetic flow around a spherical Janus particle. For all cases the zeta potential on the microchannel wall is $-15$ mV, the non-dimensionalized external electric field is 200.](image)

![Fig. 5. Three dimensional steady-state electrophoretic motion of (a) a non-polarizable particle with the zeta potential of $-60$ mV on the particle surface, (b) a fully polarizable particle, (c) a Janus particle. For all cases the zeta potential on the microchannel wall is $-15$ mV, the non-dimensionalized external electric field is 200, top row at the non-dimensionalized time of $\bar{t} = t/(L/U_{ref}) = 0$, bottom row at the non-dimensionalized time of $\bar{t} = t/(L/U_{ref}) = 1/3$.](image)
trophoretic motion of the non-polarizable particle during the same period. This is due to the two vortices on the downstream side. For the Janus particle with the polarizable part facing the applied electrical field, it moves faster than the polarizable particle and even the non-polarizable particle (Fig. 5c). This is because in this case there are two big vortices in the back of the particle that are much stronger than the two small vortices on a small portion of the particle surface, at the top and the bottom of the particle. The bigger vortices act like an engine and push the Janus particle more forward.

The comparison of the effect of the applied electric field on the velocity of different types of particles is plotted in Fig. 6. As explained above, the Janus particle with the polarisable part facing the applied electric field has the highest velocity.

5.2. Three dimensional transient ICEK motion of Janus particle in different orientations

Up to this step, we compared the motion of a non-polarizable and a fully polarizable particle with a Janus particle whose polarizable part faces to the applied electric field. Recall that the direction of the applied electric field is from the inlet to the outlet of the microchannel. The results show that the direction of motion for all these three cases is from left to right. Next, we consider a Janus particle with the polarisable part facing the outlet of the microchannel, while all other conditions are the same. Fig. 7 demonstrates that the orientation of the Janus particle plays a significant and fundamental role in the particle motion: direction, and speed. We can see that if the polarizable part of the Janus particle faces to the outlet, the vortices still form on the polarizable surface and produce force to push the particle moving backwards. Fig. 7a shows the motion of the Janus particle with the polarizable section faces the outlet is toward left and the particle moves backwards slowly from the initial position (the dash line). This is because the “vortex engine” drives the particle moving against the flow. In comparison, Fig. 7b shows that the Janus particle with the polarisable part facing the inlet moves quickly to the downstream in the applied electrical field direction.

Fig. 6. Relationship between the velocity of different types of particles and the applied electric field.

Fig. 7. Three-dimensional transient motion of Janus particles with two different orientations: (a) polarizable part facing inlet (b) polarizable part facing outlet. The non-dimensionalized external electric field is 200, zeta potential on channel walls is −15 mV; zeta potential on the non-polarizable particle surface is −60 mV. The nondimensionalized time is $t = t/(L/U_{ref}) = 1/3$. 

Initial position of the Janus Particle at $t = 0s$
5.3. Zeta potential effect on vortices around Janus particle

As shown in Fig. 8, the zeta potential of the non-polarizable side of the Janus particle has significant effects on the flow field and the vortices around the Janus particle. It is difficult to see the two small vortices, near the dividing line, on the top and the bottom of the Janus particle, when the non-polarizable section has a lower zeta potential (e.g., −15 mV). Increasing the zeta potential to −60 mV and −90 mV leads to a remarkable difference in the vortices’ size and strength. Clearly the electrostatic charge on the non-polarizable part surface has important influence on the flow field and the motion of the Janus particle.

5.4. Effect of the Janus particle size on its motion

To investigate the dependence of ICEP velocity of Janus particle to the size of particle, we studied two different sizes of Janus particles, one is \( D/2 \) in diameter and the other is \( D \) in diameter. Fig. 9 shows clearly that the bigger the particle is, the faster it moves. This can be explained by considering the origin of the ICEP velocity. The bigger particle will block a bigger portion of the flow channel. For the same applied electrical field and the same channel size, the local electric field in the smaller gap region between the particle and the channel wall is stronger. Therefore, the driving force for the bigger particle’s motion is stronger. In addition, the bigger particle has more polarisable surface area that the electric body forces can affect on. Therefore, the bigger Janus particle moves faster than the smaller one.

5.5. Different portion of polarizable material in Janus particle

We simulated a Janus particle which has a different proportion of the polarizable material to the non-polarizable material, that is, the ratio is not 1 : 1. In Fig. 10b we showed a Janus particle that only a quarter of its volume is made of the polarizable materials and the rest of it is non-polarizable. From Fig. 10, it can be seen that the vortices’ pattern and size are quite different between these two cases. Because the vortices are smaller and weaker in the case of Fig. 10b, the motion of the Janus particle with a smaller polarisable part is slower than the Janus particle with a larger polarisable part. Furthermore, the zoomed views of the smaller vortices are shown in Fig. 10. Comparing Fig. 10a with Fig. 10b, it can be expected that the size of the smaller vortices will increase as the size of the polarisable part increases.

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Fig. 8. The effect of zeta potential of the non-polarizable section of the Janus particle on flow field (a) \( \zeta = -15 \text{ mV} \) (b) \( \zeta = -60 \text{ mV} \) (c) \( \zeta = -90 \text{ mV} \). In all cases the non-dimensionalized external electric field is 200, the radius of Janus particle is \( D \) and the zeta potential of microchannel wall is \(-15 \text{ mV}\).

Fig. 9. The size effect on the three dimensional transient motion of Janus particle. (a) Janus particle diameter is \( D/2 \) (b) Janus particle diameter is \( D \), the non-dimensionalized external electric field is 200, zeta potential of the channel walls = \(-15 \text{ mV}\), zeta potential of the non-polarizable particle surface = \(-60 \text{ mV}\) and the non-dimensionalized time is \( \bar{t} = t/(L/U_{ref}) = 1/3 \).
6. Conclusions

Induced charge electrokinetics deals with the interaction of applied electric field with its induced charge on polarizable materials. The induced charge and the induced zeta potential strongly depend on the applied electric field. The main characteristic of the induced charge electrokinetic flow is the vortices. In this paper we studied the 3D transient induced-charge electrokinetic motion of a heterogeneous particle with both polarizable part and non-polarizable part in a microchannel. This study reveals the role of vortices on the polarizable side of the Janus particle, pushing the Janus particle to move faster than the non-polarizable particles and the fully polarizable particles. The orientation of the polarizable part, in the front or on the back of the particle, will affect the direction of the Janus particle’s motion. The velocity of Janus particle increases with the applied electric field, but not linearly. A larger Janus particle moves faster than a smaller Janus particle.

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