A Review on the Some Issues of Multiphase Flow with Self-Driven Particles

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Abstract: Multiphase flow with self-driven particles is ubiquitous and complex. Exploring the flow properties has both important academic meaning and engineering value. This review emphasizes some recent studies on multiphase flow with self-driven particles: the hydrodynamic interactions between self-propelled/self-rotary particles and passive particles; the aggregation, phase separation and sedimentation of squirmers; the influence of rheological properties on its motion; and the kinematic characteristics of axisymmetric squirmers. Finally, some open problems, challenges, and future directions are highlighted.

Keywords: multiphase flow with self-driven particles; squirmers; aggregation; phase separation; sedimentation; review

1. Introduction

Previous investigations on multiphase flows were mainly focused on the passive particles which are just driven by fluid and external force. However, in the multiphase flow with self-driven particles, the particles are mainly driven by internal force together with some influence of fluid and external force. Meanwhile, self-driven particles inject energy into fluid so as to change the motion of the fluid and then change its own motion in turn.

Multiphase flows with self-driven particles exist in natural and engineering applications. In nature, cells (e.g., Spermatozoa, Leucocyte), bacteria (e.g., Coccus, bacillus, Spirillum, Vibrio), fungus (e.g., Ascomycota), algae (e.g., Diatom, Dinoflagellates), protozoa (e.g., Entamoeba histolytica, Paramecium), movement proteins, etc., are all self-driven particles (as shown in Figure 1). Situations including when spermatozoa pass through the mucus to fuse with an egg [1], when Escherichia coli moves to high nutrient areas inside the human body, etc., all belong to the multiphase flow with self-driven particles [2].

Figure 1. Self-driven particles in nature. (a) Spermatozoa and E. coli; (b) Spirillum; (c) Dinoflagellates.

In practice, synthesized self-driven particles contain artificial cell tissues, phosphorus-containing colloidal particles, soft field-responsive gel, catalytic particles for biodegradation, biomarkers and contrast media, miniature swimming devices and robots, etc. (as shown in Figure 2). In the presence of external fields, artificial particles become self-driven.
and obtain the abilities of targeted drug delivery, precise surgery, self-assembly, environmental modification, and water treatment; such situations also belong to the multiphase flow with self-driven particles.

![Figure 1. Self-driven particles in nature.](image1)

**Figure 2.** Synthesized self-driven particles. (a) Artificial cell; (b) biomarkers; (c) miniature swimmer.

When compared with multiphase flow with passive particles, the multiphase flow with self-driven particles involves more complex properties [3]. Firstly, the system is in a non-equilibrium state. Brownian motion of self-driven particles is caused by the interaction between random collision of fluid molecules and particles, which cannot satisfy the fluctuation–dissipation theorem that relies on the assumption that the response of a system in equilibrium to a small applied force is the same as its response to a spontaneous fluctuation, while the system consisting of fluid molecules and particles does not satisfy this assumption because of the interaction between small applied force and self-driving force. Secondly, there is a great diversity of self-driving modes which include gravity, torque, flagella driving, cilia shaking, surface deformation, chemical reaction, bubble release, electromagnetic light energy and actin aggregation and so on. Different driving modes lead to different stresses and patterns of flow, which will affect the particle motion in turn. Thirdly, there exist some abnormal characteristics such as turbulence with small Reynolds number [4], abnormal shear viscosity, weak shear hydrodynamic diffusion, biological convection, cluster structure, non-equilibrium phase transition between disordered and ordered phases, orientational ordering of quasi-liquid crystal and so on [5]. Moreover, the translational and rotational velocities of particles will deviate from the Maxwell distribution [6].

The study of multiphase flow with self-driven particles plays an important role in exploring the laws of nature and practical applications. Firstly, research on the moving mode and efficiency of a natural organism as well as the effect of environment on its kinematic characteristics can deepen the understanding of the tropism and rationality of natural selection in organisms. For example, how does the hydrodynamic interaction between organisms affect swimming efficiency? How do the different characteristics between the flows near the wall and far away from the wall influence the distribution and swimming properties of organisms? Secondly, exploring the energy conversion mechanism of self-driven particles in the flow is beneficial for the development of artificial active materials, such as cell tissue and phosphorus-containing colloid. Moreover, research on the influence of particle shapes on the flow properties contributes to the design of the miniature swimming devices and improvement of self-organization technology of rotating body in a water environment. Understanding the interaction between self-driven particles and passive particles also contributes to the development of catalytic active particles and achieving of the biodegradation of pollutants and environmental remediation in water treatment and water protection. Thirdly, exploring the influence of fluid physical property on particle motion contributes to the realization of the propagation and diffusion mechanism of active organisms in the human system, e.g., manipulating drugs to kill germs and control infections. Finding out the influence of wall surface on the properties of particle motion can ensure that particles give full play to the function of being biomarkers and contrast media, and contribute to particle localization and identification, targeted drug delivery, accuracy improvement of non-invasive surgery, screening of diseased cells and development of detection devices.
The energy injected into the fluid by self-driven particles is dependent on the particle driving modes. The self-driven particles described in this paper are the self-propelled and self-rotary particles and squirmers, which, as the most typical particles in natural and synthetic particles, directly interact with fluid by oscillating the cilia around the body. Based on the different stress applied to the fluid, squirmers can be divided into three kinds of modes, i.e., pushers (e.g., *Escherichia coli*, spermatozoa), pullers (e.g., Chlamydomonas) and neutral squirmers (e.g., paramecium), respectively.

In past research, although the research on the motion of self-propelled/rotary particles and squirmers has made some achievements, there are still some problems that have not been clarified. For example, the effect of number density ratio of self-driven particles to passive particles on the motion of passive particles was not taken into account; the settlement characteristics of squirmers under the combined influence of driving force, gravity, hydrodynamic force, wall effect and Reynolds number are not clear; the combined effect of Reynolds number, power law index, and driving modes on the swimming velocities and hydrodynamic efficiency of squirmers in shear-thickening fluids are still unknown; there is still a lack of studies taking particle volume fraction, shape factor, self-driving mode, and fluid viscosity into account to explore the formation mechanisms of self-organization of squirmers. Therefore, the following part of the paper summarizes the research progress of these related contents.

2. Interactions between Self-Propelled/Rotary Particles and Passive Particles

Self-driven particles frequently collide with passive particles in flow. For example, spermatozoa, algae, bacteria and movement proteins collide with intracellular vesicles or dead bacteria; artificial active particles collide with pollutants. There are some pieces of research on interactions between self-driven particles and passive particles. Ouyang et al. [7] studied the interaction between one self-rotary rotator and two passive particles, and found that when the rotator acted on passive particles, the Saffman force was larger than the Magnus force, which caused the passive particles to simultaneously rotate about rotator and revolve on its axis. In a small Reynolds number range, velocities of passive particles were the superposition of large amplitude and small amplitude pulsations, but the former would disappear if the Reynolds number was large enough. However, studies of interactions between a few self-driven and passive particles are insufficient to understand the properties of particle diffusion and aggregation. In addition, self-driven particles usually translate and rotate simultaneously, rather than only one of them doing so. Based on the experimental results, Kümmel et al. [8] pointed out that increasing the number of self-driven particles would change the structural and dynamic characteristics of passive particles. As the number density of passive particles increased, the particles would aggregate with a self-diffusing function (as shown in Figure 3). In their study, self-driven particles carried out translational self-diffusion under the function of electrophoresis.

![Figure 3](image-url)

**Figure 3.** (a–d): Passive particles (red) aggregated under the function of self-driven particles (blue) [8]. Adapted with permission from Kümmel et al. (2015).

Natural and synthetic self-driven particles usually move near the wall. Some papers have concluded that cells would move along the circumferential direction, Chlamydomonas cells would disperse or oscillate along the wall [9] (as shown in Figures 4 and 5), tumble of *Escherichia coli* would be restrained, Volvox would become double beat, spermatozoa
would change to backward swimming [10], and there existed three kinds of motion states for Chlamydomonas cells after touching the wall surface, i.e., escaping from the wall and swimming parallel with the wall [11].

![Figure 4](image_url) **Figure 4.** Chlamydomonas cells disperse near the wall [9]. Adapted with permission from Bechinger et al. (2016).

![Figure 5](image_url) **Figure 5.** Squirmer oscillating along the wall [9]. Adapted with permission from Bechinger et al. (2016).

Research on the influence of wall surface on the swimming properties of self-driven particles can provide benefits for controlling the natural biological and synthetic particles such as biofilm formation [12], guiding spermatozoa pass through the fallopian tube [13], biochemical sensing [14], targeting drug delivery [15], environmental modification [16], and improving the velocities of self-diffusion electrophoresis particles [17]. Breke et al. [18] discovered that hydrodynamic attraction led to Escherichia coli aggregation near the wall. However, Molaei et al. [9] believed that despite hydrodynamic attraction enhancing particle aggregation, it also appeared without hydrodynamic attraction. Near the wall, particle movements were related to the flow regime caused by the interaction between fluid and the wall, which depended on the wettability of the wall surface [19] and could be described by slip length $ls$ (as shown in Figure 6). In addition, the slip length $ls$ was close to 0 on the hydrophilic surface but a few tens of nanometers away on the smooth hydrophobic surface. Moreover, $ls$ could be increased to the micron scale on a surface coated with hydrophobic molecular film or a surface on which bubble formation took place on the inner concave place. Poddar et al. [4] found that under the condition of $ls \neq 0$, the trajectories of particles would change greatly with the increase in $ls$, and the results obtained from such cases were totally different from the case of $ls \approx 0$ [20]. The values of $ls$ changed along the wall for the rough surface [21].

![Figure 6](image_url) **Figure 6.** Slip length.

3. **Aggregation, Phase Separation and Sedimentation of Squirmers**

Natural and synthetic self-driven particles, such as Escherichia coli or Brevibacterium with honeycomb or rafted structure (as shown in Figure 7), artificial Janus granules and synthetic photoactivated colloidal particles, often show the phenomena of aggregation, phase separation and sedimentation [5,22]. Clarifying and controlling such mechanisms can help improve the capability of screening diseased cells, developing detection devices.
together with particle localization and identification. There are several explanations for the aggregation of squirmers in previous studies. Some researchers believed it was caused by Brownian motion [23,24]; some accepted that high concentration and strong driving properties led to the increase in particle collision rate [25]; some supported that it was caused by the comprehensive influence of geometric dimensions of particles, self-driven properties and collision between particles [26]; and others attributed to the hydrodynamic interactions between particles and fluid [27,28].

Figure 7. (a) Escherichia coli with honeycomb structure; (b) Brevibacterium with rafted structure.

For the particles with different phases, particle aggregation may result in phase separation. Matas-Navarro et al. [29] discovered that phase separation would be enhanced when the hydrodynamic interaction between fluid and particles was weak and would disappear when the interaction was strong. Yoshinaga et al. [30] concluded that hydrodynamic force suppressed phase separation. Phase separation is also related to the driving modes of particles. Theers et al. [31] found that pushers had the largest degree of phase separation, neutral squirmers followed and pullers were the last. However, Zottl et al. [32] and Blaschke et al. [33] discovered that neutral squirmers had the largest degree of phase separation. The reason for the different conclusions could be attributed to the different treatment of change in fluid density. If the compressibility of the flow was not considered, the fluid transport induced by squirmers would lead to the uneven distribution of fluid density. The driving characteristics of squirmers would be weakened in the areas with large fluid density, resulting in squirmers being stable within the group without phase separation. The research of [32,33] belonged to such cases, but the effect of fluid compressibility was taken into account in the research of [31]. The effect of fluid compressibility is related to the number density of particles. The above conclusions were based on the assumption that number density of particles is constant.

Near the wall, particles would present different settlement patterns, such as a stable state together with a fixed position and orientation [34], upright state together with floating above the wall [35], etc. The appearance of such states is correlated with the influence of gravity. The inertia of particles could not be ignored if settling velocities of particles were large enough [36]. Accordingly, it is necessary to explore the settlement characteristics of squirmers under the combined influence of driving force, gravity, hydrodynamic force, wall effect and inertia of particles.

4. Influence of Rheological Properties on the Motion of Squirmers

The fluid in which the microorganism lives frequently has non-Newtonian properties, e.g., Escherichia coli swims in the gastric juice, bacterium passes through the viscous-elastic barriers which are used to protect epithelia. The non-Newtonian properties of fluid contain the dependence of viscosity on shear strain rate, viscoelasticity and yield stress, etc. [37]. These characteristics make the motion of self-driven particles in non-Newtonian fluid different from that in Newtonian fluid. For example, the viscoelasticity will change the swimming stoke of particles, and elastic stress may affect the swimming velocities of particles. The existence of high molecular weight and macromolecules will increase the viscosity and further reduce the velocities of particles [38], while the interaction between driving property of self-driven particles and rheology of fluid may improve the velocities
of particles [39–41]. Understanding the influence of rheological properties on the motion of self-driven particles is helpful to manipulate drugs to wipe out germs and control infection.

When squirmer swim in a fluid with viscosity varying with shear rate, the velocity and hydrodynamic efficiency, which is defined as the value of the useful to the total work, are related to the change of viscosity and driving mode caused by fluid shear. In the shear-thinning fluid, the non-local effect caused by the change of flow is more important than that of local viscosity reduction on its swimming [42]. The change of squirmer velocity depends on its starting velocity [43]. Compared with swimming in Newtonian fluid, although squirmer swim slowly, they swim more efficiently [44]. The power consumption of squirmer swimming decreases with the increase in Reynolds number, and the hydrodynamic efficiency is the same at a small Reynolds number for pullers and pushers [45]. The squirmers near the wall collide periodically with the wall with a constant period [46] and will change its trajectory due to rotation in parallel and opposite motion collisions [47].

Another property of non-Newtonian fluid is viscoelasticity. In the viscoelastic fluid, self-driven particles can not only paddle, but also move by the elasticity of fluid [48]. The change of squirmer motion caused by viscoelasticity is related to the driving mode. Whether the pullers and pushers move towards the wall depends on their initial position, while the neutral squirmer does not depend on the initial position [49]. The residence time of a squirmer in the near-wall region depends on the fluid elasticity and the initial position [50]. The elasticity of the fluid makes it easier for a squirmer to move towards the wall [51]. The degree of drift caused by viscoelasticity depends on the Deborah number, and ratio of driving velocity to flow velocity and driving mode [52]. The velocity of a squirmer decreases with the addition of Brinkman medium, but the hydrodynamic efficiency increases [53]. Viscoelasticity of fluid strengthens the rotational diffusion [54]. Squirmers move faster in a third-order viscoelastic fluid than in a Giesekus fluid [55]. Viscoelasticity of fluid slows down and speeds up the pullers and pushers, respectively, but it has no effect on neutral squirmers [56]. Squirmers consume more energy in Newtonian fluid and has higher hydrodynamic efficiency in viscoelastic fluid. For squirmers swimming in upper-convected Maxwell/Oldroyd-B fluids, the elastic stress becomes singular at a critical Weissenberg number [57]. However, the singularity is removed when the exponential Phan–Thien and Tanner model is utilized [58]. The above research was based on the Stokes flow with zero or minimum Reynolds number, i.e., the inertia effect is neglected. In fact, many flows are beyond the range of the Stokes flow [59]. Therefore, the influence of elastic number, which represents the ratio of elasticity to inertia, on squirmer velocity and hydrodynamic efficiency remains to be studied.

5. Characteristics of Suspension Flow of Axisymmetric Squirmers

Natural and synthetic self-driven particles are not limited to spherical shapes. Axisymmetric shape is a typical shape except for sphere, such as protozoa (e.g., Ciliata), biopolymer (e.g., Myoglobin, movement proteins), Bacillus (e.g., Bacillus subtilis, Escherichia coli) in nature and some synthetic self-driven particles (as shown in Figure 8).

![Figure 8](image_url)  
(a) Ciliata; (b) Bacillus; (c) miniature artificial swimming devices; (d) artificial Janus granules.

The study of the shape effect on the flow with self-driven particles is helpful to deepen the understanding of the natural selection tendency of some organisms and the design of micro artificial swimming devices. The non-isotropic shape of axisymmetric particles
leads to more complex motion modes and abundant self-organization phenomena, e.g., the swimming and feeding changes were found to be more significant in oblate spheroids than prolate spheroids [60]. For spherical squirmers, the self-organization phenomenon is caused by the interference and blocking between squirmers, but the self-organization of axisymmetric squirmers is caused by its array formed by the interactions. For example, Bacillus subtilis forms polar clusters [61]; Bacteroides dendritic moves along the narrow, long and high-density zone [62]; Tubulin-dynamin forms vortex arrays [63]; and Escherichia coli forms long range array [64].

Axisymmetric particles are more prone to self-organization than spherical particles. Moreover, shape-induced phase separation will occur at low Peclet numbers. However, whether the direct contact between particles or the long-range hydrodynamic effect is the main reason for the self-organization of squirmers has been debated. Based on the Langevin dynamics simulation of columnar [65] and filamentous squirmers [66], it was found that the formation of self-organization is dominated by the interactions between squirmers. Moreover, Brownian dynamics’ simulation considering long-range hydrodynamic action [67] also captured the self-organization. However, Pandey et al. [68] believed that particle shape and long-range hydrodynamic force were the factors to form the self-organization.

It has been found that suspension flow of axisymmetric squirmers is more prone to turbulence than that of spherical one [5]. It is generally believed that the turbulence emergence of particle suspension is related to the Peclet number. When the Peclet number is large, i.e., convection is stronger than diffusion, turbulence is more likely to appear. However, it was found that there is no turbulence when the Peclet number in the suspension flow of axisymmetric squirmers is as high as 50 [69]. Therefore, there are other factors at work, e.g., the hydrodynamic interactions, rotating dipoles formed by rotating flagella bundle and a counter-rotating body propulsion of squirmers [70], and induced circular motions [71] on the surface. Reinken et al. [72] pointed out that axisymmetric squirmers had a stronger rotation effect than spherical ones; the coupling of rotation and translation made turbulence appear. If the axisymmetric squirmers are asymmetric along the axis, the order of its orientation would be weakened, which also leads to turbulence [73]. Therefore, the factors leading to turbulence of suspension contain Peclet number, squirmer flexibility, hydrodynamic interactions, effects of strong rotation, anteroposterior asymmetry of squirmers, and self-driving modes. Thus, it is important to explore the correlation between various factors and turbulence.

6. Conclusions and Prospects

In this paper, the interaction between self-propelled/self-rotary particles and passive particles, the aggregation and phase separation of squirmers, the effect of sedimentation and rheological property on the motion of squirmers, and the characteristics of suspension with axisymmetric squirmers are reviewed. The following research can be carried out in the future:

(1) For the interactions between self-propelled/self-rotary particles and passive particles, the following issues should be focused on: the dynamic characteristics and configuration of the passive particles; the critical parameters of configuration transformation under different parameters; and the trajectory and morphology of self-propelled/self-rotary particles near the rough wall with variable roughness element.

(2) For the aggregation, phase separation and sedimentation of squirmers, the following issues should be focused on: the characteristics of aggregation and phase separation of squirmers under different driving modes; the distribution of cluster scale, mean cluster scale for pushers, pullers and neutral squirmers under different parameters; the characteristics of sedimentation under the combined action of different parameters; and the settlement trajectory and morphology under different parameters.

(3) For the influence of rheological property on squirmer movement, the following issues should be focused on: the motion of squirmers in a shear-thickening fluid; the hydrodynamic efficiency under different parameters; the characteristics of squirmer motion
in a viscoelastic fluid by taking inertia into account; and the motion modes and velocity variation near the wall with different Weissenberg numbers and elasticity numbers.

(4) For the suspensions with axisymmetric squirmers, the following issues should be focused on: the characteristics of self-organization of the axisymmetric squirmers group; the turbulent characteristics of suspension with axisymmetric squirmers; and the root mean square of flow and squirmers velocity, Reynolds stress, and probability density function of orientation under different parameters.

(5) Scientists have put effort into computational studies on hydrodynamic interactions of self-driven particles. The immersed boundary–lattice Boltzmann method and the direct-forcing fictitious domain method are the main methods in the studies of multiphase flow with self-driven particles. Both methods have been successfully applied to the study of Newtonian fluid. When the methods are applied to viscoelastic fluid, especially the fluid with a large Weissenberg number, there will be a stress boundary layer. Therefore, how to choose the appropriate discrete scheme is worth studying.

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