

# Apparent wall-slip of colloidal hard-sphere suspensions in microchannel flow



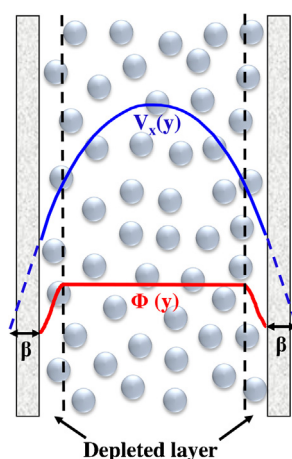
S. Ghosh, D. van den Ende, F. Mugele, M.H.G. Duits\*

Physics of Complex Fluids group, Department of Science and Technology, MESA<sup>+</sup> Institute, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

## HIGHLIGHTS

- Wall slip affects transport of colloidal suspensions through microchannels.
- Depletion of particles near the channel walls causes apparent slip.
- For colloidal hard spheres, the apparent slip length increases strongly with volume fraction.
- This trend is well described by a simple model that translated local concentration into a local viscosity.

## GRAPHICAL ABSTRACT



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## ABSTRACT

We investigated the dependence of the apparent slip length ( $\beta$ ) on the particle concentration for suspensions of colloidal hard spheres flowing through microchannels with smooth walls. Hydrostatic pressure was used to pump monodisperse suspensions of 1  $\mu\text{m}$  silica spheres in water–glycerol mixture through a poly(dimethylsiloxane) microchannel with rectangular cross section. Confocal scanning laser microscopy allowed accurate measurement of velocity profiles via particle tracking velocimetry. Apparent slip lengths were measured by extrapolating the velocity profiles to zero. Systematic variations were made of the particle volume fraction  $\Phi$  (0.03–0.42) and the Peclet number (2–50). In these regimes the apparent slip length shows a weak dependence on  $Pe$  and the slip velocity near the wall grows linearly with shear rate irrespective of  $\Phi$ . However,  $\beta$  turns out to increase strongly with  $\Phi$ , tending toward an asymptotic behavior for  $\Phi \gg 0.3$ . To explain these observations, we worked out a conceptually simple model, in which the apparent slip is caused by a local reduction in volume fraction due to excluded volume, and the local viscosity is calculated using the Krieger–Dougherty equation. The predictions by this model match the experimental results remarkably well.

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\* Corresponding author.

E-mail address: [m.h.g.duits@utwente.nl](mailto:m.h.g.duits@utwente.nl) (M.H.G. Duits).

## 1. Introduction

Colloidal and non-colloidal suspensions are used in variety of applications, such as pharmaceuticals, food products, paints, cosmetics, ceramics, etc. For many of these products, knowledge of the flow behavior and especially the slip behavior near the wall is essential for safe and optimum processing. Also applications where particle suspensions have to flow through meso/microscopic pores, like filters or microfluidic channels, can be affected by slip. Slip essentially reduces the drag coefficient for fluids flowing through a confined geometry, thereby enhancing the flow rate. In the measurement of rheological properties such as the shear viscosity, the occurrence of slip clouds the measurement, necessitating either mitigation or quantitative correction [1]. The presence of a smooth wall and the absence of strong particle-wall adhesion are generally considered as factors that favor slip.

Wall-slip has been identified not only with particulate suspensions but also with molecular liquids, and several attempts have been made to quantify the slip in those systems using different measurement techniques [2–16]. In general it is found that for Newtonian liquids, the slip length depends on the interaction of liquid molecules with the substrate: wetting surfaces favor a no-slip condition whereas partially wetting or non-wetting surfaces cause noticeable slip. But the slip in molecular liquids, which occurs due to repulsive interactions of liquid molecules with the substrate, differs fundamentally from the ‘apparent’ slip found in suspensions. For particulate fluids, slip occurs due to the formation of a low viscous lubrication layer. Since the particles cannot penetrate the hard wall, flowing suspensions can under certain conditions expel a film of solvent, with a film thickness comparable to the particle size. The corresponding lowering of the particle concentration then causes a reduction in the local viscosity, and hence a larger velocity gradient across this thin layer. Linear extrapolation of the velocity profile of the homogeneous suspension to the location of the wall then results in a finite velocity, which is often termed as the “apparent slip velocity” [17]. We remark that this definition of “apparent slip” differs from the concept of “true slip” as can occur in polymeric melts (with no solvent available for lubrication), or “friction slip” [18] which involves a Coulomb-friction mechanism.

While the formation of a thin molecular film can occur irrespective of the particle concentration, the importance of slip, i.e., the magnitude of the apparent slip length can be expected to depend on the particle volume fraction. In a (very) dilute system, the relative viscosity  $\eta_r$  of the bulk suspension will not be very different from unity; the effect of particle depletion near the wall will then be relatively small. For high bulk concentrations corresponding to  $\eta_r \gg 1$  the effect should be much stronger. Also additional mechanisms leading to particle depletion near the walls could play a role, like shear-induced structural changes in the fluid.

Most studies aimed at slip in (concentrated) suspensions were performed with large, non-Brownian particles [16,17,19–23] showing a liquid-like or solid-like collective behavior. In their studies on dense suspensions of irregularly shaped particles, Yilmazer and Kalyon [19] found that the (normalized) apparent slip length  $\beta$  scaled with the suspension viscosity:  $\eta_r/8 \leq \beta/a \leq \eta_r/4$ ,  $a$  is typical particle radius. Jana et al. [17] also reported a similar scaling for large hard-sphere systems ( $2a = 90 \mu\text{m}$ ) at  $\Phi \geq 0.45$ , which they modeled with a shear-induced migration of the particles [24,25] in Couette flow. However they did not observe significant slip for  $\Phi \leq 0.40$ .

Considering the large amount of work on non-Brownian particles, it is remarkable how little emphasis has been given to colloidal suspensions (even for the model case of hard spheres). Using rheo-microscopy Ballesta et al. [10,26] observed predominant slip behavior for concentrated ( $\Phi = 0.58$ ) colloidal dispersions, and quantified a yielding transition from this. They also found a

qualitative similarity between the slip behavior of concentrated suspensions of soft particles [27,28] below the yield stress, and a Bingham-type slip response. Another study with Brownian suspensions ( $\Phi = 0.28$ ) for several particle sizes of O (100 nm) by Kok et al. [12] reported measurable wall-depletion effects at shear rates corresponding to a Peclet number of O (1). At lower  $Pe$ , where the timescale of the Brownian motion is shorter than that of the flow, the fluid can maintain the equilibrium structure in spite of the flow. However, a systematic study of the (apparent) slip length as a function of both  $\Phi$  and Peclet number has been missing so far; most studies dealt with the slip response near the glass transition.

In the present study, we determine the apparent slip length of monodisperse suspensions of  $1 \mu\text{m}$  silica spheres suspended in water–glycerol mixture using confocal microscopy. This fluid can be regarded as a (nearly) hard sphere system. Analysis of image–time series obtained with a confocal scanning laser microscope with particle tracking, allows accurate measurement of the velocity profile near the wall. Systematic variation is made of the volume fraction (from 0.03 to 0.42), and the Peclet number (from 2 to 50). The measurements are compared to predictions from a model that accounts for the particle depletion near the wall using a simple geometric argument.

## 2. Theoretical modelling

Experimentally we measure the apparent slip length  $\beta$  based on the Navier boundary condition which relates the slip velocity ( $v_w$ ) at the solid–liquid interface to the shear rate ( $\dot{\gamma} = \frac{\partial v_x}{\partial y}$ ) tangentially applied on the surface:

$$v_w = \beta \left. \frac{\partial v_x}{\partial y} \right|_{y=y_w} \quad (1)$$

accordingly,  $\beta$  is the distance to the wall at which the fluid velocity extrapolates to zero (Fig. 1). Slip becomes an important phenomenon if the magnitude of  $\beta$  becomes comparable to the length of the flow geometry, e.g., the gap between two rheometer surfaces or width of the microchannel.

Our experimental observations are compared with a simple model considering just an excluded volume interaction between a spherical particle with radius  $a$  and a flat wall. In this model we assume: (i) the particle velocity is equal to the velocity of the suspension and (ii) the semi-empirical equation by Krieger and Dougherty [29] also holds for boundary layer. The model ignores spatial correlations between particles, and hence assumes that the volume fraction is equal to the bulk concentration ( $\Phi_\infty$ ) for all  $y$  coordinates, except in a transition zone  $0 < y < 2a$  near the wall. In this zone, a local volume fraction is defined as the fraction of solid in a thin slice parallel to the wall, with a thickness  $dy \ll a$ . For the case of hard spheres, this concentration profile  $\Phi(y)$  is expressed as (see Appendix):

$$\Phi(y) = \Phi_\infty f(y) = \Phi_\infty \left( \frac{y}{2a} \right)^2 \left( 3 - 2 \left( \frac{y}{2a} \right) \right) \quad (2)$$

To calculate the local viscosity  $\eta(y)$  in the transition zone (the ‘lubrication layer’) from  $\Phi(y)$ , we insert the latter into the Krieger and Dougherty [29] equation, which gives a good description of the viscosity of hard sphere suspensions:

$$\eta(\Phi(y)) = \eta_0 \left[ 1 - \frac{\Phi(y)}{\Phi_m} \right]^{-\frac{5}{2} \Phi_m} \quad (3)$$

where  $\eta_0$  is the solvent viscosity and  $\Phi_m$  is the maximum packing fraction of particles. The factor  $5/2$  in the exponent ensures that Einstein’s expression [30] is recovered in the limit of low volume fractions.

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