P3 – Drag reduction by DNA-grafting for single microspheres in a dilute λ-DNA solution

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The fluid resistance of single micrometre-sized blank and DNA-grafted polystyrene microspheres under shear flow is compared in purified water and dilute λ-DNA solutions by means of optical tweezers experiments with a high spatial (±4 nm) and temporal (±0.2 ms) resolution. The measurement results show that the drag experienced by a colloid in a dilute λ-DNA solution (molecular weight of 48502 bp per molecule, radius of gyration of 0.5 μm) is significantly decreased if the microsphere bears a grafted DNA brush. This newly discovered drag reduction effect is studied for different parameters, comprising the molecular weight of the grafted DNA molecules (250 bp, 1000 bp and 4000 bp), the concentration of the λ-DNA solution (11, 17 and 23 μg ml^{-1}, all being significantly smaller than the critical entanglement concentration c^*), the microsphere core diameter (2 μm, 3 μm and 6 μm) as well as the flow speed of the medium (10 to 50 μm s^{-1}). The maximum extent of the drag reduction is found to amount to (60±20)% compared to the λ-DNA-induced contribution on the drag acting on blank colloids. We propose a theoretical explanation of this effect based on the combination of the drift diffusion model of Rauscher and co-workers [2] and the stagnation length theory of polymer brushes, as it was established by Kim, Lobaskin *el al.* [3]. In particular, the solution of the Stokes equation (i.e., the Navier-Stokes equation for creeping flow) for the studied system yields a numerical prediction that is found to be in full accord with our experimental results within measurement uncertainty.

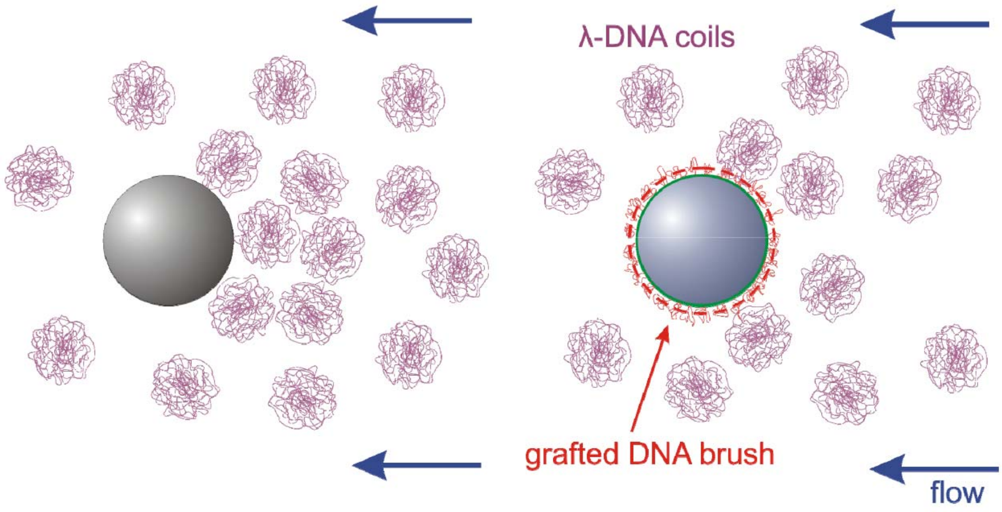

Fig. 1. Schematic of the drag reduction effect.

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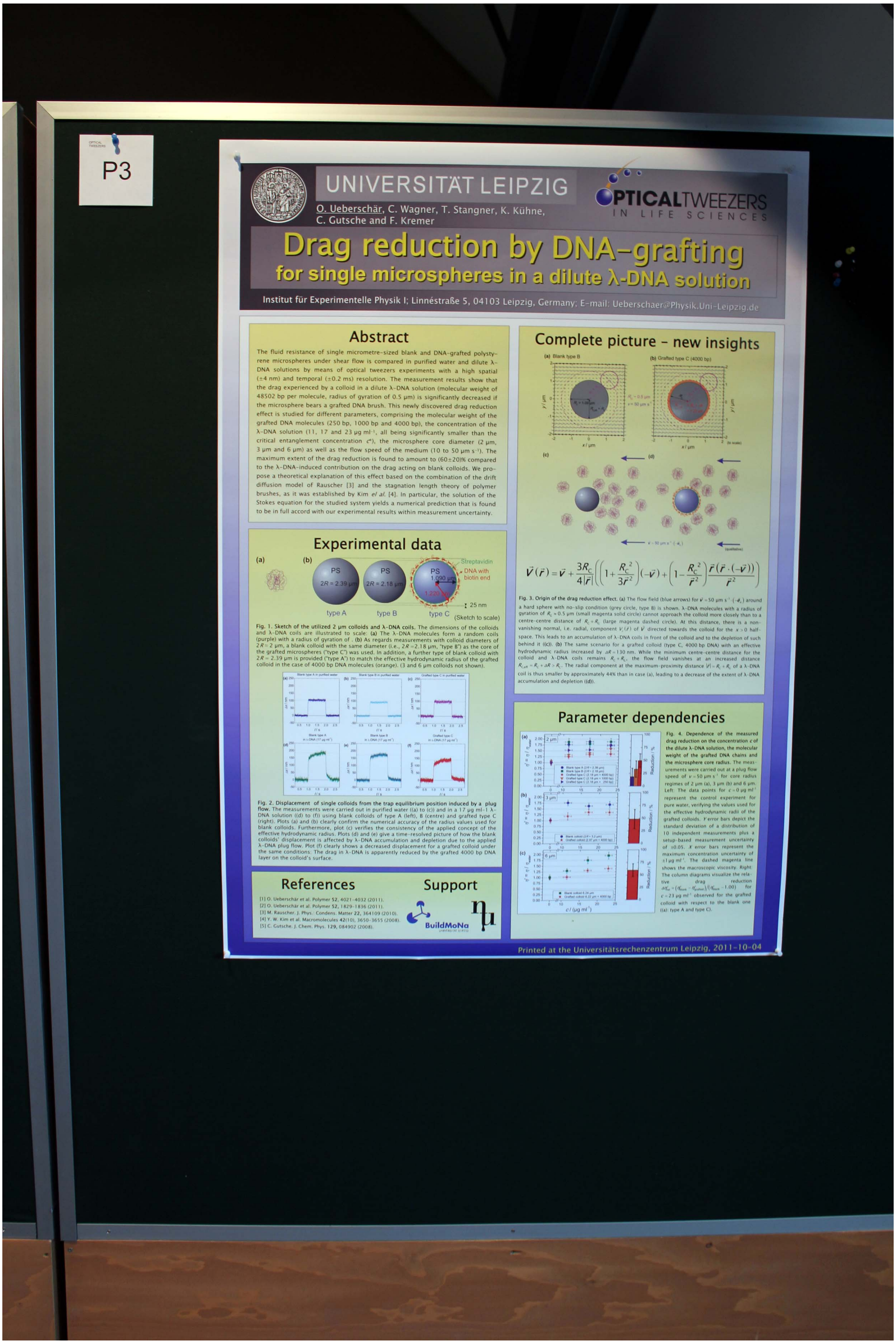

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Abstract

The fluid resistance of single micrometre-sized blank and DNA-grafted polystyrene microspheres under shear flow is compared in purified water and dilute λ-DNA solutions by means of optical tweezers experiments with a high spatial (±4 nm) and temporal (±0.2 ms) resolution. The measurement results show that the drag experienced by a colloid in a dilute λ-DNA solution (molecular weight of 48502 bp per molecule, radius of gyration of 0.5 µm) is significantly decreased if the microsphere bears a grafted DNA brush. This newly discovered drag reduction effect is studied for different parameters, comprising the molecular weight of the grafted DNA molecules (250 bp, 1000 bp and 4000 bp), the concentration of the λ-DNA solution (11, 17 and 23 µg ml⁻¹, all being significantly smaller than the critical entanglement concentration c^*), the microsphere core diameter (2 µm, 3 µm and 6 µm) as well as the flow speed of the medium (10 to 50 µm s⁻¹). The maximum extent of the drag reduction is found to amount to (60±20)% compared to the λ-DNA-induced contribution on the drag acting on blank colloids. We propose a theoretical explanation of this effect based on the combination of the drift diffusion model of Rauscher [3] and the stagnation length theory of polymer brushes, as it was established by Kim *et al.* [4]. In particular, the solution of the Stokes equation for the studied system yields a numerical prediction that is found to be in full accord with our experimental results within measurement uncertainty.

Experimental data

Fig. 1. Sketch of the utilized 2 µm colloids and λ-DNA coils. The dimensions of the colloids and λ-DNA coils are illustrated to scale: (a) The λ-DNA molecules form a random coils (purple) with a radius of gyration of . (b) As regards measurements with colloid diameters of $2R = 2$ µm, a blank colloid with the same diameter (i.e., $2R = 2.18$ µm, "type B") as the core of the grafted microspheres ("type C") was used. In addition, a further type of blank colloid with $2R = 2.39$ µm is provided ("type A") to match the effective hydrodynamic radius of the grafted colloid in the case of 4000 bp DNA molecules (orange). (3 and 6 µm colloids not shown).

Fig. 2. Displacement of single colloids from the trap equilibrium position induced by a plug flow. The measurements were carried out in purified water ((a) to (c)) and in a 17 µg ml-1 λ-DNA solution ((d) to (f)) using blank colloids of type A (left), B (centre) and grafted type C (right). Plots (a) and (b) clearly confirm the numerical accuracy of the radius values used for blank colloids. Furthermore, plot (c) verifies the consistency of the applied concept of the effective hydrodynamic radius. Plots (d) and (e) give a time-resolved picture of how the blank colloids' displacement is affected by λ-DNA accumulation and depletion due to the applied λ-DNA plug flow. Plot (f) clearly shows a decreased displacement for a grafted colloid under the same conditions: The drag in λ-DNA is apparently reduced by the grafted 4000 bp DNA layer on the colloid's surface.

References

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$$\vec V(\vec r) = \vec v + \frac{3R_C}{4|\vec r|}\left(\left(1+\frac{R_C{}^2}{3\vec r^{\,2}}\right)(-\vec v) + \left(1-\frac{R_C{}^2}{\vec r^{\,2}}\right)\frac{\vec r\,(\vec r\cdot(-\vec v))}{\vec r^{\,2}}\right)$$

Fig. 3. Origin of the drag reduction effect. (a) The flow field (blue arrows) for $\vec v = 50\ \mu m\ s^{-1}\cdot(-\vec e_x)$ around a hard sphere with no-slip condition (grey circle, type B) is shown. λ-DNA molecules with a radius of gyration of $R_G = 0.5$ µm (small magenta solid circle) cannot approach the colloid more closely than to a centre-centre distance of $R_C + R_G$ (large magenta dashed circle). At this distance, there is a non-vanishing normal, i.e. radial, component $V_r(\vec r)$ of $\vec V$ directed towards the colloid for the $x > 0$ half-space. This leads to an accumulation of λ-DNA coils in front of the colloid and to the depletion of such behind it ((c)). (b) The same scenario for a grafted colloid (type C, 4000 bp DNA) with an effective hydrodynamic radius increased by $\Delta R = 130$ nm. While the minimum centre-centre distance for the colloid and λ-DNA coils remains $R_C + R_G$, the flow field vanishes at an increased distance $R_{C,eff} = R_C + \Delta R > R_C$. The radial component at the maximum-proximity distance $|\vec r| = R_C + R_G$ of a λ-DNA coil is thus smaller by approximately 44% than in case (a), leading to a decrease of the extent of λ-DNA accumulation and depletion ((d)).

Parameter dependencies

Fig. 4. Dependence of the measured drag reduction on the concentration c of the dilute λ-DNA solution, the molecular weight of the grafted DNA chains and the microsphere core radius. The measurements were carried out at a plug flow speed of $v = 50$ µm s⁻¹ for core radius regimes of 2 µm (a), 3 µm (b) and 6 µm. Left: The data points for $c = 0$ µg ml⁻¹ represent the control experiment for pure water, verifying the values used for the effective hydrodynamic radii of the grafted colloids. Y error bars depict the standard deviation of a distribution of 10 independent measurements plus a setup-based measurement uncertainty of ±0.05. X error bars represent the maximum concentration uncertainty of ±1 µg ml⁻¹. The dashed magenta line shows the macroscopic viscosity. Right: The column diagrams visualize the relative drag reduction $\Delta\eta'_{rel} = (\eta'_{blank} - \eta'_{grafted})/(\eta'_{blank} - 1.00)$ for $c = 23$ µg ml⁻¹ observed for the grafted colloid with respect to the blank one ((a): type A and type C).

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