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Mass transfer enhancement due to a soft elastic boundary

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ABSTRACT

Electrochemical mass transfer experiments are performed in a channel in which one wall is made of a soft polymer gel. Mass transfer is enhanced up to 25% relative to rigid walls when the ratio of viscous to elastic forces on the gel increases above a critical value. The enhancement is attributed to a hydrodynamic instability occurring at the fluid–gel interface. The results suggest that soft elastic boundaries could serve as a mechanism for improving mixing and transport in the laminar flows characteristic of microfluidic devices and other small-scale geometries.

1. Introduction

Miniaturization of chemical processes has brought opportunities and challenges. One of the key challenges is how to promote efficient mixing and transport when fluid phases are flowing in micron-scale or smaller geometries (Stone et al., 2004; Squires and Quake, 2005). Fluid flow is generally laminar under these conditions, so turbulence is not present to aid mixing and transport. Instead, other ways must be found to disrupt fluid particle paths from the relatively ordered structure that they have in simple laminar flows. Many recent studies have attempted to do this through modifying the geometry through which the fluid flows, thereby creating chaotic fluid particle paths in a flow that is still laminar. Examples include the use of herringbone-like grooves on channel walls, channels with a twisted geometry, and flexible walls actuated by an external source (Hessel et al., 2005).

In this paper, we demonstrate a different approach for improving mass transfer in laminar fluid flows within confined geometries: the use of a soft elastic boundary which is set into motion through a hydrodynamic instability driven by the adjacent fluid flow. Originally motivated by observations of dolphin swimming, research on hydrodynamic instabilities at the interface between a flowing fluid and a flexible solid boundary has had a long history (Riley et al., 1988; Gad-el-Hak, 2003). As dolphins are efficient swimmers, many hypothesized that the compliance of their skin inhibits high-Reynolds-number boundary-layer instabilities that would otherwise occur near a rigid surface. Numerous theoretical and experimental studies show that flexible boundaries can indeed suppress such instabilities (Riley et al., 1988; Gad-el-Hak, 2003), thereby offering a potential route to reduction in the hydrodynamic drag. The opposite effect can also occur: flexible boundaries can enhance the instability of an already unstable flow or even induce instability in a flow that would be stable in the absence of wall flexibility. The latter is especially relevant to the low-Reynolds-number flows characteristic of microfluidic devices and other small-scale geometries.

In the absence of inertia, simple shear flow of a Newtonian fluid between two parallel plates is stable to perturbations of any magnitude since no mechanism is present to cause an instability. (Stability can also be inferred by noting that time is absent from the governing equations.) If one of the walls is replaced by an elastic solid, however, then the flow can be unstable to small-amplitude disturbances. Theoretical and experimental studies show that instability occurs when a dimensionless stress, $\tau = \mu U/RG$, is greater than a critical value that depends on the fluid-to-solid thickness ratio and interfacial tension (Kumaran et al., 1994; Kumaran and Muralikrishnan, 2000; Gkanis and Kumar, 2003; Eggert and Kumar, 2004). Here, μ is the fluid viscosity, U is the characteristic flow velocity, R is the fluid thickness, and G is the shear modulus of the elastic solid. The parameter τ thus represents a ratio of viscous forces to elastic forces. Instability arises due to amplification, by the flowing fluid, of disturbances at the fluid–solid interface, with time entering the problem through the continuity-of-velocity boundary condition at that interface.

Although the destabilization of fluid flows by a soft elastic boundary has been extensively studied, the extent to which such an unstable flow can enhance mixing and transport has not been addressed.

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If such enhancement is significant, then soft elastic boundaries could find applications in microfluidic devices and other technologies. How such mass transfer enhancement can be achieved is detailed in the experiments described next.

2. Experimental details

The experimental apparatus is shown schematically in Figs. 1 and 2. The flow channel, shown in Fig. 1, was created by carving a cavity into each of two polycarbonate blocks, placing the blocks together, and sealing with a rubber gasket. The channel was 10 cm long, 4 cm wide, and 1.5 mm high. The electrolyte, consisting of $0.01\,M\,K_4\,Fe(CN)_6 + 0.01\,M\,K_3\,Fe(CN)_6 + 0.5\,M\,KOH$ in glycerol (Mahinpey and Trass, 2005), was pumped through the flow channel using a gear pump (Cole Parmer, model no. 75211-3; gear set: Micropump/Idex, model no. GB-P35 JVSAB1). The 3 cm × 1 cm working and counter-electrodes were cut out of platinum sheet (Aldrich, 0.05 mm thick, 99.9+% purity) and glued to the channel walls away from the ends to minimize edge effects. The gels were placed on the counter-electrode. A saturated calomel electrode, serving as the reference, was placed in a solution of 0.5 M KOH in glycerol. A universal programmer (EG & G Parc; model no. 175) and potentiostat (EG & G Princeton Applied Research; model no. 363) were used to generate the voltage sweep needed to identify the limiting current plateaus.

The gels were made by mixing silicone elastomer base and curing agent (Sylgard 182) in different ratios in Petri dishes and curing the mixture in a vacuum oven at 70 °C for 2 h. The shear moduli of these gels were measured in a parallel-plate rheometer (Rheometrics; model no. Ares LS714306). The relatively low moduli of the gels along with the high viscosity of the glycerol-based electrolyte enable us to generate values of τ large enough so that viscous forces are comparable to elastic forces ($\tau \sim 1$).

The cell was installed in the apparatus shown in Fig. 2. The experiments were conducted at room temperature (22–23 °C). The Reynolds number UH/ν varied from 0.1 to 60, where U is the average velocity in the channel, H is the height of the channel above the gel, and ν is the kinematic viscosity of the fluid. The Peclet number, UH/D with D being the diffusion coefficient, was generally greater than 1000, so that the system was convection-dominated.

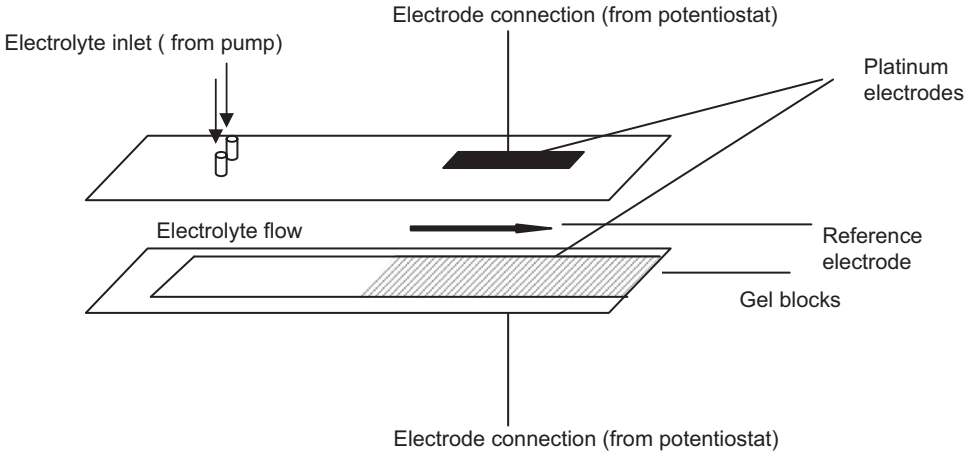

Fig. 1. Schematic of flow channel.

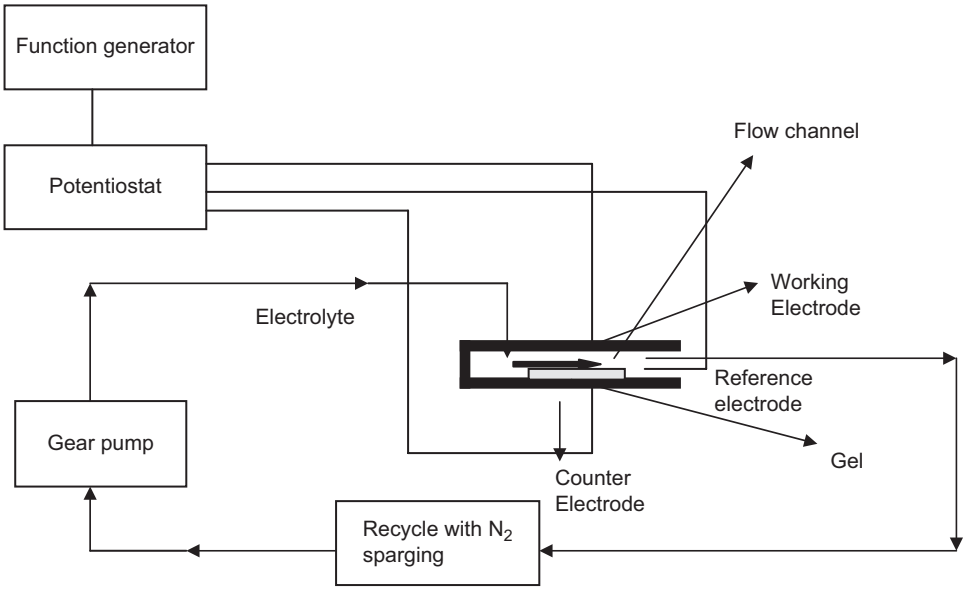

Fig. 2. Schematic of experimental apparatus.