Drag reduction and enhanced mixing in flows using ultrahydrophobic surfaces

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Under laminar, microscale flow conditions drag reduction and rapid mixing can be difficult to achieve. In these low Reynolds number flows in the absence of turbulence there are currently no viable techniques to reduce drag. In addition, mixing rates in these flows are governed by molecular diffusion and in the absence of enhanced mixing techniques, mixing lengths and residence times can be much longer than most applications will allow. The ability to significantly reduce drag or mixing time could potentially result in savings for a number of small devices and could have great impact in the future as mechanical technology is miniaturized, and biomedical analysis moves towards lab-on-chip technology.

A series of experiments will be presented which demonstrate significant drag reduction for the laminar flow of water through microchannels using hydrophobic surfaces with well-defined micron-sized surface roughness. These ultrahydrophobic surfaces are fabricated from silicon wafers using photolithography and are designed to incorporate precise patterns of microposts or microridges. These micropatterned surfaces are then modified through a chemical reaction with an organosilane to make them hydrophobic. An experimental flow cell is used to measure the pressure drop as a function of the flow rate for a series of microchannel geometries and ultrahydrophobic surface designs. We will show that pressure drop reductions up to 40% and apparent slip lengths up to 25μm can be obtained using ultrahydrophobic surfaces. The drag reduction is found to be independent of flow rate and to increase monotonically with increasing micropost/microridge spacing and decreasing microchannel width. Measurements of the deflection of an air-water interface that is formed between microposts and supported by surface tension using a confocal surface metrology system will be presented. This shear-free interface reduces the flow resistance by allowing the fluid to contact only a very small effective area of the silicon surface. Micro particle image velocimetry measurements (μ-PIV) of the velocity field are presented which demonstrate that slip velocities of more than 50% the mean velocity can be achieved just above shear-free air water interface as seen in Figure 1. These results compare very well with to the results of numerical simulations.

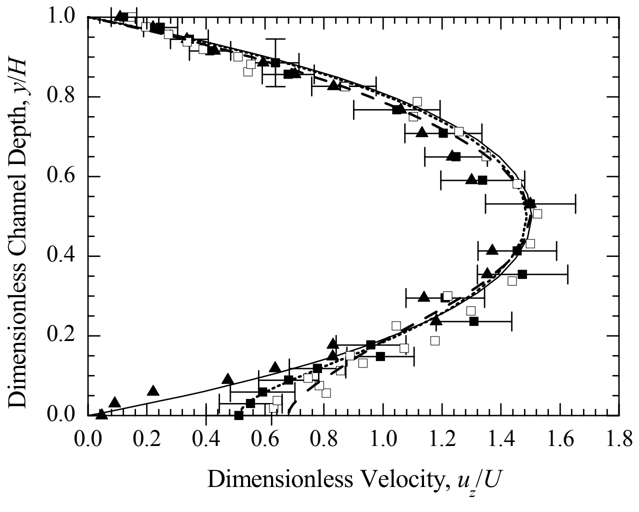

Figure 1: Direct comparison of the velocity profiles measured through μ-PIV (symbols) and predicted from numerical simulations (lines) for the flow through an 85μm tall channel past a series of ultrahydrophobic surfaces contain 30μm wide microridges spaced 30μm (solid symbols) and 60μm (open symbols) apart. The data include velocity profile for a vertical slice taken above the center of microridge (▲), above the center of 30μm shear-free interface (■), and above the center of 60μm shear-free interface (□).

We will demonstrate that by aligning the microridges and therefore the air-water

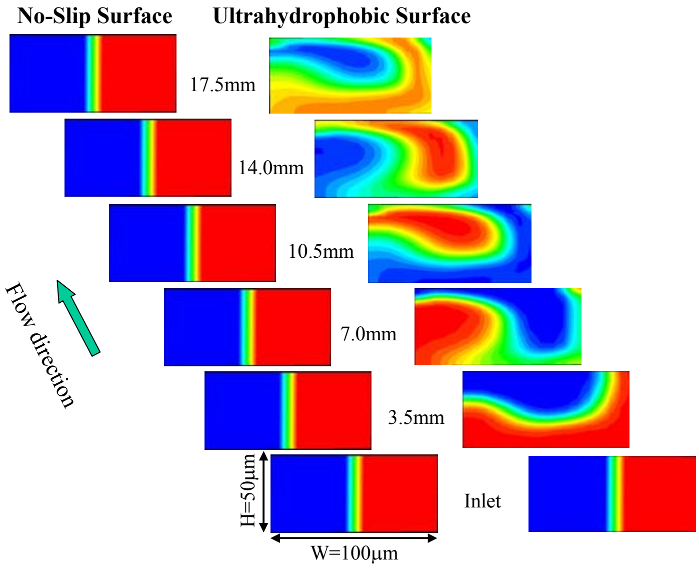

Figure 2: Numerical simulation of helical flow induced by the presence of 30μm wide ultrahydrophobic microridges spaced 30μm apart and aligned at a 45 degree angle to the flow direction. These simulations agree quite well the experimental measurements.

interface at an oblique angle to the flow direction, a secondary flow is generated which is shown to efficiently stretch and fold the fluid elements and reduce the mixing length by more than an order of magnitude compared to that of a smooth microchannel. A Y-channel was used to bring two streams of water together, one tagged with a fluorescent dye. As seen in Figure 2, a confocal microscope was used to measure fluorescence intensity and dye concentration and μ-PIV was again used to characterize the flow. Increasing the angle of the microridges was found to reduce the mixing length up to a critical angle of about 60° beyond which the mixing length is found to increase with further increases to the angle of the microridge.

Given enough time, we will demonstrate how this technology can be extended to reduce drag in turbulent flows and discuss some of the challenges for optimizing ultrahydrophobic surfaces for different applications.