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Micro-Scale Flow on Natural and Engineered Functional Surfaces

The deposition and controlled flow of continuous thin liquid film droplets on surfaces containing complex micro-scale surface patterning (either man-made or naturally occurring) plays a key part in numerous engineering and biologically related fields. For example, in an engineering context, complex surface patterning is present in processes involving printing/photolithography [1] and the application of precision protective coatings [2]; in biological systems they occur in such diverse areas as plant disease control [3], in redistribution of lung linings in respiratory systems [4], and in sustaining life itself, as in the unusual case of the Namibian desert beetle which drinks by harvesting morning mists [5] -- the mist condenses on hydrophilic bumps on its upper surface to form larger droplets which then roll down waxy hydrophobic channels between the bumps to reach the beetle's mouth.

Lubrication theory is used to model gravity-driven continuous thin liquid film flow and droplet motion over complex naturally occurring and engineered functional surfaces. The associated time dependent, nonlinear coupled set of equations, for the film thickness/drop-height and pressure, are solved using a purpose written portable, object orientated, parallel, time-adaptive full approximation storage (FAS) multigrid algorithm in order to maximise computational efficiency when fine-scale resolution is needed to obtain accurate, mesh independent solutions at the micro-scale.

Shown in Figure 1 is the flow of a gravity-driven thin pesticide laden (water) film of asymptotic thickness of 100 μm over a digitally mapped partial maple leaf surface topography inclined at 30° to the horizontal. The complex leaf morphology contains varying elevated surface features ranging up to 100 μm in height, the same order as the thickness of the coated film, over a square domain of width 20.40 mm in each direction. The solution was obtained using over 263,000 grid points in 881 seconds on a dual 2.8 GHz Quad-Core Intel Xeon node utilising 6 processors, automatically dividing the computational domain into near equal sized virtual topologies to optimize computational cost and resources. The free-surface profile, illustrated in the upper part of Figure 1, reveals the successful coating of a thin pesticide film over the naturally complex topography with maximum positive and negative planar disturbance away from the asymptotic film thickness of 30% and 2%, respectively, located at the ridge just upstream (A) and the valley downstream (B) as indicated in the lower part of Figure 1. Such variations in pesticide film thickness uniformity are significant in practice since they have an important influence on the efficacy of leaf coatings for plant disease control [3].
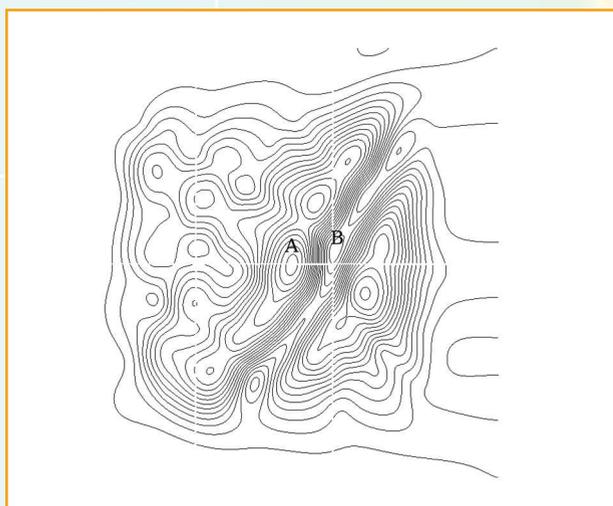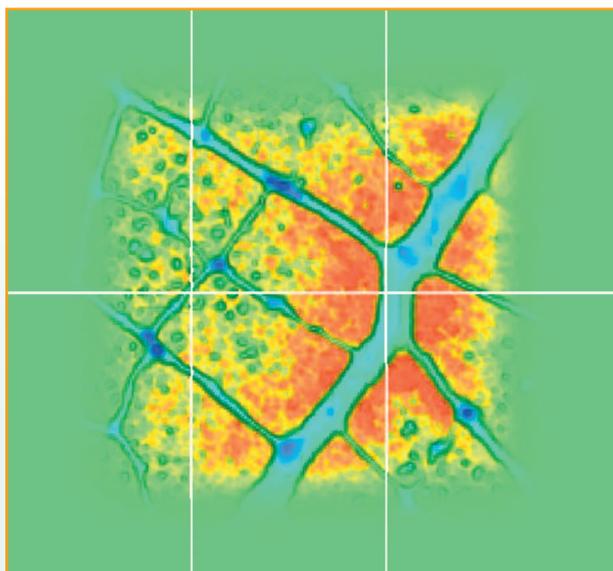
Thin liquid free-surface film flows are important components of many micro/nano-manufacturing systems. One important example is in the use of photolithography for the manufacture of displays and screens where free-surface disturbances caused by light-emitting polymers must be within strictly controlled tolerances [6]. Figure 2 shows the flow of a polyimide photoresist over a substrate during the fabrication of a thermoelectric microdevice. The

Figure 1: (upper) Digitally mapped partial leaf surface (20.4 mm x 20.4 mm) subdivided onto a virtual computational topology for solution using 6 processors. (lower) resultant steady-state free-surface iso-contour profile of thin film flow over the complex leaf surface topography. Viscosity of 0.001 Pa s, density of 1000 kg m^{-3}, and surface tension of 0.07 Nm^{-1}.

incoming thin film is assumed to be uniform with 20 μm at the inlet on the left of the domain. It flows over a sub-structure of the micro-device which is inclined at 30° to the horizontal. The topographical features, shown in the top of Figure 2, were created using combinations of simple primitives. The problem was solved on a square computational domain with over 1.3 million nodes on 8 processors.

Figure 2 illustrates the resultant free-surface profile of a thin polyimide photoresist which takes the form of a *"dancing man"*. It shows that the distribution of the localised micro-interconnects have an adverse effect on the overall free-surface profile and thus planarisation of the film; with peaks and depressions occurring in the vicinity of the five large but thin interconnecting wings -- the highest being the northern wing, W1 (a 10.6% increase from the uniform film height) and the lowest at the western wing,

W5 (a 8.6% increase). Notably, the individual free-surface disturbances produced by the small but taller micro-interconnects constituting the body of the dancing man (shown in expanded form in Figure 2), whose size are of the same order as the flow's capillary length scale, result in a combined ridge formation that is surprisingly lower than the surroundings, leading to an increase of only 7.4% relative to the uniform film height. The largest free-surface depression occurs downstream past the south eastern interconnecting wing, W3, with a deviation of 3.1% from planarity.
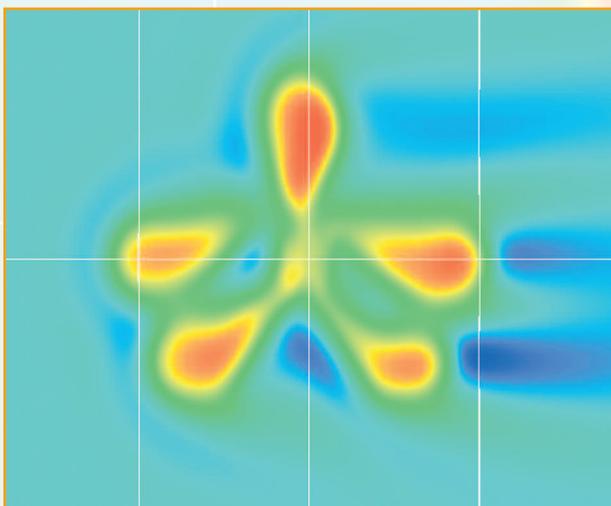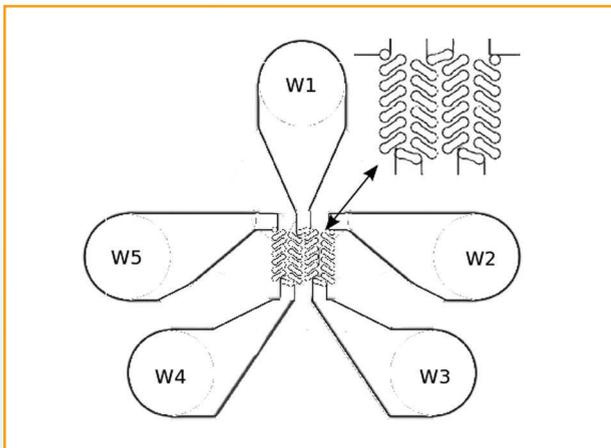

Figure 2: (top) "Dancing man" geometrical sub-design of part of a complex thermoelectric micro-device (7.5 mm x 6.5 mm) with external inter-connects of diameter 1.5 mm and thickness 2 μm. Also shown is a schematic of the micro-interconnects patterned diagonally, each of length 270×10^{-6} m and height 4 μm with 60 mm diameter ends; (bottom) colour map of the resultant free-surface disturbance. (Flow from left to right).

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