KNUDSEN-PUMP-BASED MICRO-HOVERCRAFTS

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ABSTRACT

We introduce polymer-membrane micro-hovercrafts which utilize incident light to generate the lift force. The light is absorbed by a carbon nanotube layer on one side of the membrane resulting in a temperature gradient along the thickness of the membrane, which in turn pumps air under the membrane via the mechanism of thermal transpiration. The hovercrafts float over a substrate at heights of $\sim 50 \mu\text{m}$, which agrees with the predictions of our theoretical model.

INTRODUCTION

The term “micro-flyer” is often used as a misnomer to describe centimeter-scale robotic systems that achieve sustained flight [1, 2]. However, the scaling of traditional propeller-based aircraft to dimensions of less than 1 cm, let alone the true micro scale, is extremely challenging [1], possibly requiring new flight mechanisms at the millimeter or micron scales. As a recent possible approach, the Knudsen force was used to make microscopic polycrystalline silicon plates hover and jump above microfabricated resistive heaters [3, 4]. Here, we show that commercially available nano-porous membranes can hover above flat surfaces using thermal transpiration, which is also known as the Knudsen pump effect. When illuminated by light, the membranes can hover a few tens of microns above any flat surface, rather than only above a microheater.

PRINCIPLE OF OPERATION

Thermal transpiration, also known as thermal creep, is the flow of gas along channel walls that feature a temperature gradient along the length of the channel [5, 6]. The gas typically flows from the cold reservoir towards the hot reservoir (Fig. 1), which can be used to create a Knudsen pump [7]. If the bottom side of a porous membrane absorbs light more effectively than the top, thermal transpiration through the pores (channels) can be controlled by simply heating the membrane with a controlled light input. The resulting Knudsen pumping will push the gas under the membrane, floating the membrane above the surface on an air bearing, similar to toy pucks on air hockey tables.

Figure 1: Schematic of thermal transpiration phenomenon at atmospheric pressure.

ASSEMBLY AND CHARACTERIZATION

10- μm -thick Sterlitech polycarbonate membranes are used as the basis for our micro-hovercrafts. These membranes feature hole diameters in the 80-100 nm range with a spacing of $\sim 0.5 - 1 \mu\text{m}$. Crucially, the membranes are poor thermal conductors, with a manufacturer-reported thermal conductivity of $0.20 \text{ W}/(\text{m}\cdot\text{K})$. Similar thermally insulating porous membranes have shown the ability to pump gas using the Knudsen pump effect [7] at atmospheric pressure.

We coated one side of the membranes with carbon nanotubes to act as an absorbing layer which created the temperature difference required for thermal transpiration. To minimize thermal stress-induced deflection, some of the membranes were glued to a microfabricated silicon ring. This ring was $200 \mu\text{m}$ tall with a wall thickness of $50 \mu\text{m}$. Figure 2 shows a photograph of the microfabricated silicon ring and a scanning electron micrograph of the membrane.

Figure 2: A) Picture of microfabricated Si ring which can be added for rigidity and flatness B) SEM pictograph of a membrane's surface with pores showing as dark circles.

THEORETICAL MODEL

The mass flow rate through a long tube due to a temperature gradient between two large reservoirs can be expressed as [5, 8]:

$$\dot{M}^{tb} = -\alpha P + \gamma \Delta T, \quad (1)$$

where P is the over-pressure under the membrane, ΔT is the temperature differential between the top and bottom surfaces and α and γ are functions derived using numerical data presented by Sharipov [8] for varying levels of rarefaction. The generated over-pressure distribution can be modeled by equating the downward flow through the membrane to the radial outward flow underneath the membrane. Assuming Poiseuille flow underneath the patterned membrane, the over-pressure profile can be obtained by solving the differential equation:

$$-\frac{d^2 P}{dr^2} - \frac{dP}{dr} \left(\frac{1}{r} \right) + \frac{8FF\alpha\mu P}{\sqrt{3}\rho h^3 b^2} = \frac{8FF\gamma\mu\Delta T}{\sqrt{3}\rho h^3 b^2}, \quad P(R) = 0, \quad P'(0) = 0, \quad (2)$$

where h is the gap height, FF is the geometric fill factor, ρ is the air density, μ is the air viscosity, R is the radius of the hovercraft membrane, and b is the pitch between the tubes. The imposed boundary conditions assure that at the edge of the patterned disk, the over-pressure goes to zero, so that it equals the surrounding environmental pressure. Additionally, it is assumed that over-pressure profile flattens at the center of the disk due to the radial symmetry. Assuming that the membrane and the air in the pores

conduct heat in parallel, the temperature difference between the top and bottom surfaces of the disk can be expressed as:

$$\Delta T = \frac{LeI(6b^2 - \sqrt{3}a^2\pi)}{6b^2\kappa_{pc} + \sqrt{3}a^2\pi(\kappa_{air} - \kappa_{pc})} \quad (3)$$

where a is the tube radius, L is the membrane thickness, ϵ is the carbon nanotube film absorbance (assumed to be approximately 90%), I is the incident optical flux and κ_{pc} and κ_{air} are the thermal conductivities of the polycarbonate membrane and air, respectively.

The lift force can be calculated by integrating the resulting over-pressure distribution over the surface of the disk. Figure 3 shows the generated lift force as a function of the height. The gap heights that can be achieved by micro-hovercrafts can be found by equating the lift force to the weight of the membrane, and are on the order of 50 μm above a substrate.

Figure 3: Estimated lift force generated by membranes with various pore diameters and pitch (solid curves). The dashed line shows the estimated device weight. The maximum height that can be achieved is represented by the intersection of the force line with the dotted estimated weight of the micro-flyer.

TESTING RESULTS

Testing of the micro-hovercrafts was performed at atmospheric temperature and pressure conditions and inside of a glass enclosure to minimize the effects of the ventilation currents in the room. A 100-watt LED array was used as the light source. Figure 4 shows the testing setup.

Figure 4: Schematic of the testing setup from the microscope camera point of view.

Figure 5 shows a progression of screenshots from a test flight. Numerous test flights have shown heights in the range of ~30-80 μm , consistent with the predictions of our theoretical model. The lift force and the hovering heights can be optimized further by using membranes with other pore diameters and spacing.

Our results demonstrate that low-thermal-conductivity porous membranes/films can float under illumination, opening new possibilities for levitating MEMS sensors and microflyers at the millimeter and micron scales.

Figure 5: Sequential screenshots of video showing a hovering test flight (A→B→C). The 100- μm thick underlying substrate serves as a reference for in-flight gap height measurements using a microscope camera setup.

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