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DESIGN AND EXPERIMENTAL CHARACTERIZATION OF A THERMOSTRESS-BASED MEMS GAS SENSOR

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Knudsen force, thermostress convection, gas sensor

ABSTRACT

Thermal stresses in rarefied gases offer novel applications in gas sensing and actuation for microsystems. These high-order non-equilibrium effects are significant when the characteristic length scale of the thermal gradients within the gas become comparable to the molecular mean free path, conditions which are readily achievable in MEMS devices[1]. The Microscale In-Plane Knudsen Radiometric Actuator (MIKRA) exploits these effects for the purpose of gas pressure and composition sensing in low-pressure binary mixtures. The device features a suspended shuttle mass above an underlying substrate which displaces laterally away from a series of fixed heated arms under the action thermal stresses. In this configuration the stresses are referred to as Knudsen forces. The heated arms contain platinum filaments deposited over their upper surface, allowing the temperature gradient in the gap to be precisely regulated. Shuttle deflection is sensed via an array of comb capacitors located near the periphery. Through a separate set of comb drive actuators the suspension stiffness of the device is calibrated, allowing force magnitude to be estimated. A SEM image of the device with labeled components and dimensions is provided in Fig.1.

Shuttle deflection is sampled over a range of pressures between approximately 75 mTorr and 113 Torr for heating element powers of 75, 100, and 125 mW. Device temperature during actuation is measured using a thermal imaging microscope. Temperature contours in air are shown in Fig.2 at a pressure of 75 mTorr and power of 100 mW. Nominal gap between heater and shuttle arms is 20 μm, confirming the presence of a thermal gradient on the order of 10^6 K/m, sufficient magnitude to facilitate production of thermostress convection. Experimental data showing the non-dimensional Knudsen force coefficient as a function of the Knudsen number in the gap is provided in Fig.3. Here, the Knudsen force coefficient is defined as

$$C_F = \frac{FT_\infty}{P_\infty A \Delta T}$$

where F is the Knudsen force magnitude, T_∞ is the ambient gas temperature, P_∞ is the ambient gas pressure, A is the area of the gap-facing shuttle arm, and ΔT is the temperature difference between the fixed and shuttle arms. The shuttle response reveals a non-monotonic transition between the free molecular (Kn > 10) and continuum (Kn < 0.01) flow regimes, a behavior which stems from the bimodal nature of the thermostress convection. In the free molecular regime the force arises from ballistic interaction of the molecules on the shuttle surface and output is linear with pressure[2]. Conversely, near the continuum limit the force varies inversely with pressure and results from thermal stresses within the

gas[3]. The non-dimensional force coefficient data may be used to estimate performance of a scaled actuator of similar geometric configuration, allowing working range to be extended to either higher or lower pressures.

Device sensitivity to gas composition is also demonstrated using air and helium as the working fluids. Results reveal a simultaneous force peak location and magnitude shift between the species, a behavior stemming from the differences in molecular mean free path between gases. Combined with the monotonically varying heating element resistance the thermostress convection mechanism can be used to simultaneously resolve gas pressure and composition in transitional rarefied flows provided the mixture is binary. Such a capability is attractive in a host of industrial applications such as process monitoring in the lyophilization of food and pharmaceuticals.

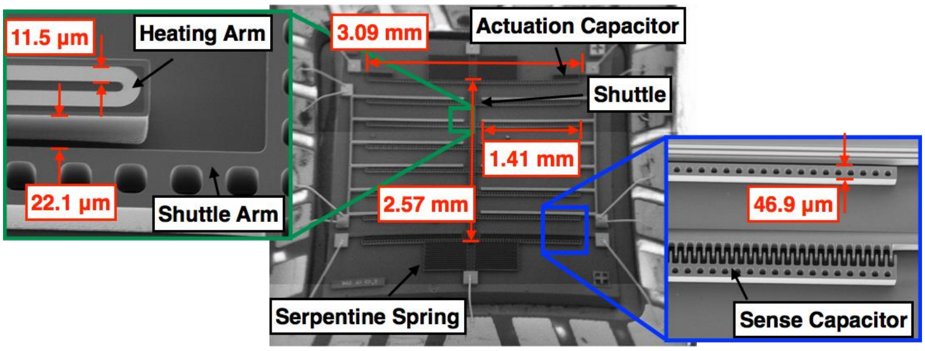

Figure 1: SEM image of MIKRA device with labeled components and dimensions

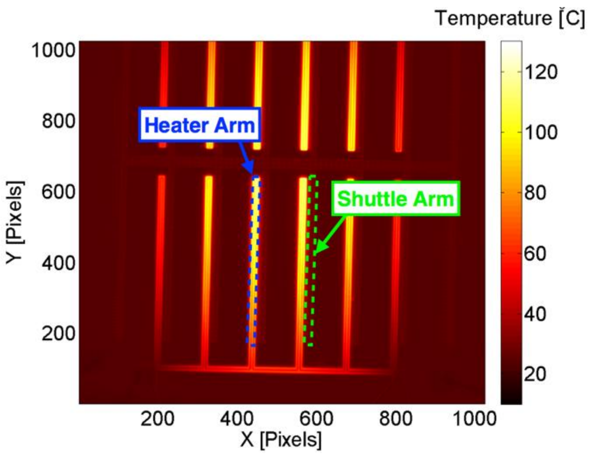

Figure 2: Temperature distribution at 75 mTorr, 100 mW

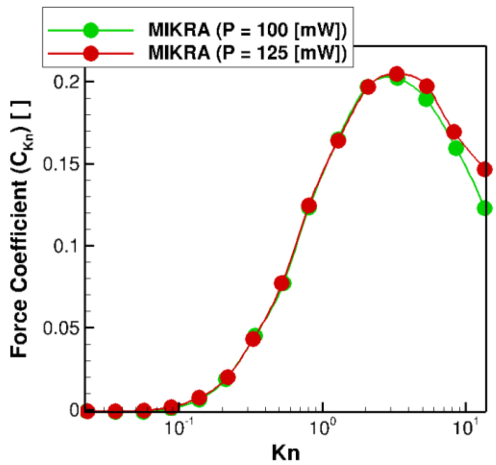

Figure 3: Measured force magnitude and deflection

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