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Characterization of liquid and gaseous micro- and nanojets using microcantilever sensors

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Abstract

This paper reports the development of microelectromechanical metrology tools to characterize liquid and gaseous jets generated from microfabricated nozzles with diameters ranging from 1 to 12 μm. Microcantilever sensors with either piezoresistive elements or integrated heating elements have been fabricated and applied to measure thrusts, velocities, and heat transfer characteristics of micro/nanojets. Piezoresistive cantilever measurements showed that liquid butane microjets from a 6 μm diameter nozzle achieved velocities 40–60 m/s for driving pressures 0.6–1.4 MPa. Jet velocities estimated from cantilever measurements agreed well with shadowgraphy results within 12.5% without any correction factor. A microcantilever with integrated heating elements measured cooling capacities of liquid butane microjets on the order of 10^{-5} W/K.
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1. Introduction

Micro/nanoscale jets have potential applications in drug delivery [1], microsurgery [2], inkjet printing [3], microelectronics cooling [4,5], and precision manufacturing [6]. While O(100–1000 μm)-scale high speed gaseous jets have been investigated as potential actuators for flow control applications, little work has been reported on free liquid and gaseous jets having characteristic scales that extend below 10 μm the jet diameter becomes comparable to or even smaller than the wavelength of the light source employed, optical metrology such as particle image velocimetry (PIV) and laser Doppler velocimetry may not be viable. Hot-wire anemometry (HWA) has been miniaturized using microfabrication techniques [7] but its size is still comparable to or larger than the nozzle diameters, such that hot-wire sensors could not be fully submerged into micro/nanoscale flows. Moreover, the hot-wire is generally too fragile to be interfaced with liquid jet environment. Flow visualization techniques such as Schlieren photography, interferometry, and shadowgraphy are also challenging even for the liquid jets that have a distinctive refractive index compared to the ambient.

Microfabricated cantilevers have become perhaps the most widely used transducer for sensing and actuating at the nanometer scale [8] with the major application being atomic force microscopy (AFM). In AFM operation, a force can bend the cantilever and the amount of deflection is recorded using various mechanisms such as optical sensing [9,10], piezoresistive sensing [11,12], capacitive sensing [13], and thermal sensing [14,15]. Besides AFM application, microfabricated cantilevers have been employed for acceleration sensing [16], bio/chemical detection [17–20], radio frequency microelectromechanical systems (MEMS) switches [21], local control of chemical vapor deposition processes [22], and nanoscale deposition of solid materials [23,24].

Recently, microcantilevers also have been used as metrology tools to measure fluid properties and investigate flow characteristics. Micromachined silicon cantilever beams have been applied in liquid flow volume sensing [25,26] and highly sensitive

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piezoresistive cantilevers have been introduced for measuring air flow velocity in a small pipe [27]. Microcantilevers immersed in viscous fluid have been characterized [28] and applied to measure viscous drag [29]. AFM cantilever based anemometers have been designed to measure gas and liquid flows with high spatial and temporal resolution and demonstrated turbulent flow measurements in both air and water [30]. Due to their high deflection sensitivity and small minimum detectable deflection in the sub-nanometer regime, microcantilevers are promising candidates for micro/nanojets flow characterization.

Among microcantilever sensing mechanisms, piezoresistive and thermal sensing are best suited for liquid and gaseous jets environment. With the liquid jet impingement, optical sensing using a laser and position sensitive diode could generates spurious signals due to the refraction in the liquid around the cantilever. Capacitive sensing usually requires electrode structures that could block the jet flow and limit cantilever deflection. Free standing structures are preferred for micro/nanojets metrology since they can be fully exposed to the jet environment. Piezoresistive sensing is well suited for deflection, thrust, and velocity measurement for both liquid and gaseous micro/nanojets. Since a commercial piezoresistive cantilever was readily available, it was introduced to verify the working concepts. After that, customized piezoresisitve cantilevers were fabricated considering problems associated with the commercial cantilevers.

For heat flux measurements of micro/nanojets, another type of cantilever which has an integrated heating element (heated cantilever) was introduced. The heated cantilevers were originally developed for data storage [31,32], but have recently been redesigned and fabricated at Georgia Tech to extend their functionality. By mimicking HWA, the heated cantilever can interrogate the cooling capacity of micro/nanojets by monitoring heat transfer between the integrated heating element and micro/nanojets environment.

Based on previously reported work [33], this paper presents novel metrology applications of microfabricated cantilevers to investigate micro/nanojets flow. The jets were generated from micromachined silicon nozzles defined in the chip plane, connected to a small-scale pressurized reservoir [34]. Liquid butane and gaseous nitrogen jets ejected from 1 to 12 μm diameter nozzles have been characterized with the microcantilever sensors. Piezoresistive cantilevers were used to extract jet thrust and velocity from the measured beam deflection and heated can-

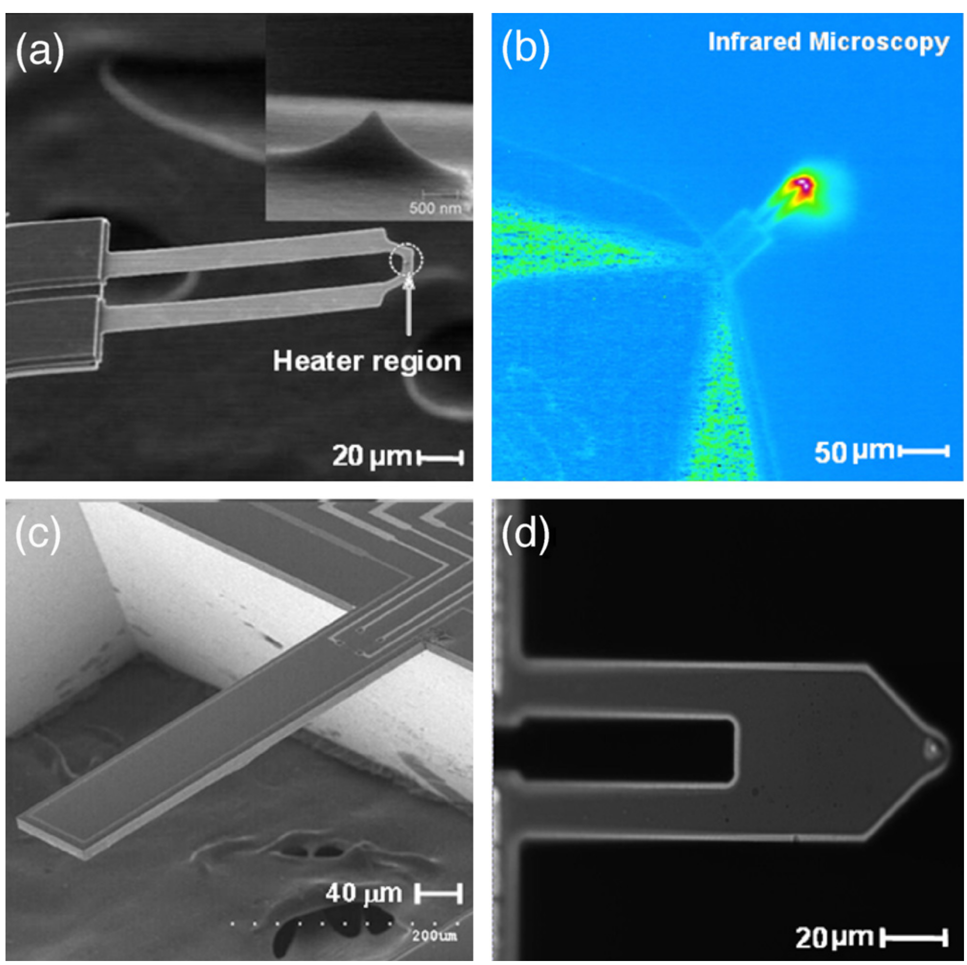

Fig. 1. (a) SEM micrograph of a fabricated heated cantilever; (b) IR micrograph of the fabricated heated cantilever with electrical heating; (c) SEM micrograph of a fabricated piezoresistive cantilever; (d) optical micrograph of a commercial piezoresistive cantilever.

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