NanoJets – Formation, Characterization and Applications

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Project Objectives

The NIRT *Nanojets* focuses on experimental and numerical investigations of the flow physics of nanometer-scale jets and their application to surface modification. The program builds on recent molecular dynamics simulations, revealing the formation of nanojets with velocities of up to 400 m/s by pressurized injection of liquid propane through nanometer-scale nozzles (Moseler and Landman, *Science* **289** (2000) 1165). The goal of the NIRT is to grow these activities towards experimental realization.

To this end, novel nano/microfabrication processes are used to produce the jet drivers and nozzles and diagnostics probes for assessment of their integral properties. The global nanojet flow and nanojet flow impingement will be characterized using atomic force microscopy (AFM), AFM-based anemometry and resonant microbalances. These measurements are combined with detailed atomistic molecular dynamic simulations to provide insight into nanometer-scale structural features and dynamics of the nanojet flow. The fundamental research will lead to the implementation of nanojets for direct write lithography, enanling printing of nanoscale features for e.g. data storage, integrated circuitry, molecular electronics, and nanosensors.

The nanojet program thus bridges between the basic science of nanojets and the engineering design, fabrication of nanojet devices, experimental characterization of the nanojets, and their utilization for printing of nanoscale features. In face of the relentlessly accelerating miniaturization of devices, as well as in light of fundamental problems pertaining to the dynamics of the jet close to breakup, that is when the jet diameter approaches the molecular size and the commonly used continuum fluid dynamics treatments are of questionable validity, it is imperative to investigate theoretically and experimentally these issues.

Project Results

During the first project year, the research has focused on the micro/nanofabrication of components for the nanojet devices and the generation and characterization of micrometer-size jets. Even though distinctly larger in size, the microjets provide necessary insight in the challenges to be expected during nanojet generation and allow the PIs to develop and test the required metrology tools in an early project phase. In parallel with the experimental work, the molecular dynamics simulations have been extended to the, from an application point of view, important jet injection into non-vacuum.

Nanojet Simulation

Molecular dynamics simulations were performed for the propagation of propane nanojets (6nm in diameter, see Fig. 1) in the presence of nitrogen gas (T = 150 K, density = 3.4 kg/m^3 = 0.073 N_2 atoms/ nm^3). Compared to nanojets injected into vacuum, the propagation velocity of the front of the jet decreases by about 30%, but the break-up length of the jet remains essentially the same. Molecular dynamic (MD) simulations at various ambient gas densities and temperatures are in progress.

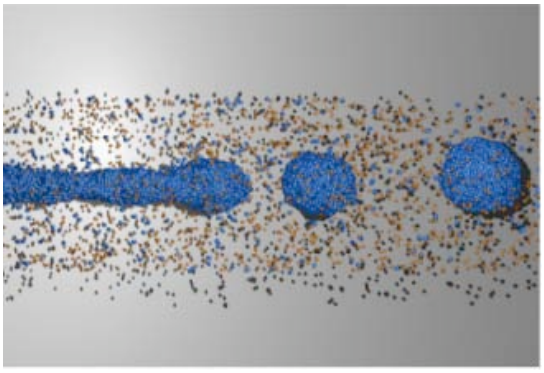

Fig.1*: Molecular dynamic simulation of 6nm diameter nanojet injected into N_2.*

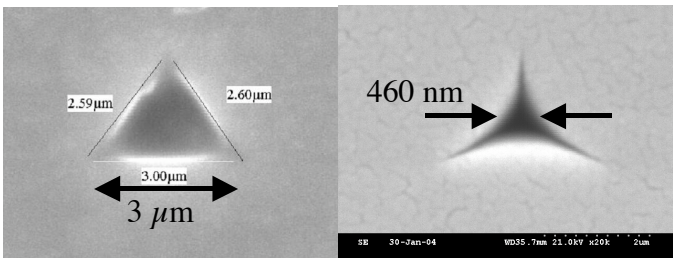

Fig. 2*: (a) Triangular nozzle resulting from KOH etching; (b) same nozzle after oxidation*

Nanojet Fabrication

The overall structure, from which the nanojets are ejected, consists not only a nano-orifice but also of a fluid reservoir connected to a shaped nozzle. The nozzle has to be mechanically strong enough to withstand the required pressure. Unlike previous approaches focusing on out-of-plane fabrication schemes, in-plane fabrication techniques have been investigated. In-plane nozzles allow flexibility to define the shapes and dimensions of the nozzle channel and reservoir, allow for the nozzle to withstand high-pressure drops, and simplify packaging. The nozzles are fabricated using a variety of micromachining steps including anisotropic wet and dry etching, silicon fusion bonding, and oxidative sealing. Nozzles as small as 460 nm have been successfully fabricated (see Fig. 2).

Nanojet Characterization

To be able to generate liquid propane and butane jets, a fluidic system based on a pressurized reservoir, to which the jet nozzle is directly connected, has been developed. The maximum operating pressure of the present system is 34.5 MPa (5,000 psi). With this first generation system, jets generated from both stainless steel and silicon nozzles with diameters down to 1 μm are currently investigated.

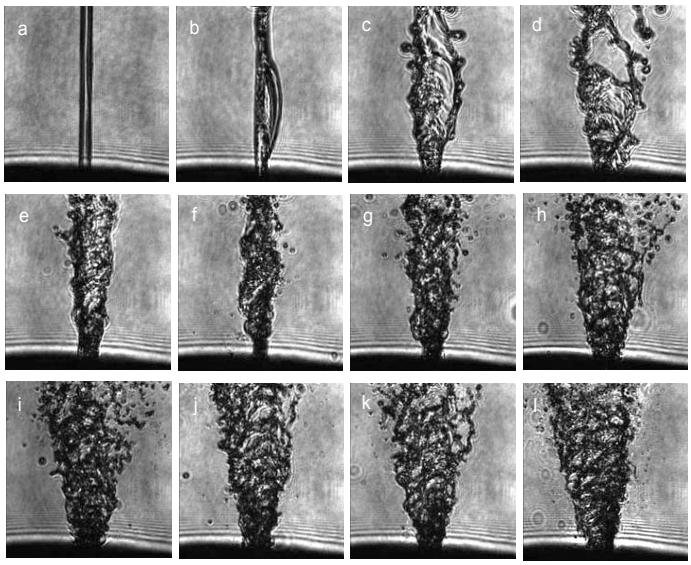

Fig. 3: *Images taken of liquid butane jets with increasing reservoir pressure (from 0.17MPa to 2.07MPa in equal increments in a-k). The nozzle diameter is 10 µm.*

The jet flow is visualized using a shadowgraph technique. The flow field is illuminated using a (double-pulse) ND:Yag laser (532 nm) where the duration of the laser pulse is on the order of 5ns. Instantaneous images of the flow are captured using a PIV CCD camera having 1008 x 1018 pixels equipped with a high-magnification microscope lens. The smallest field of view currently measures 28 μm on a side (i.e., approximately 28 nm per pixel).

Initial flow investigations show that the global features of the jet change substantially as the reservoir pressure increases (and with it the jet speed). Figures 3a-l show the effects of the increase in jet speed on its characteristics. In each of these images, the field of view is 200 μm on the side and the nozzle diameter is 10 μm. In these images, the reservoir pressure is increased from 0.17 MPa (Figure 3a) to 2.24 MPa (Figure 3l) in equal increments. Apparently, the jet undergoes a spectacular breakup when the reservoir pressure exceeds 0.52 MPa (Figure 3c and d), but as the pressure increases further, the jet column appears to develop smaller-scale instabilities that lead to its atomization (Figure 3e, 0.86 MPa). As the pressure increases further, the cross-stream spreading rate of the jet column increases substantially with jet speed. From these data it is estimated that when the reservoir pressure is 2.24MPa (Figure 3l), the jet speed around $x/D = 10$ is 66m/sec.

Silicon microcantilevers have been used to interrogate with the microjets and measure the thrust and heat flux characteristics of microscale high-speed evaporating liquid jets that are injected into a quiescent gaseous medium having variable ambient pressure. Thrust measurements are performed with commercial piezoresistive cantilevers having a spring constant of 1.37 N/m and a calibrated deflection sensitivity of 0.4 mV/V per μm. The cantilevers have been mounted on separate three-axis micropositioners such that they can be traversed around and through the microjet. The investigated liquid butane microjets have a diameter of 7-16 μm and temperature of -20 °C. The piezoresistive cantilevers are calibrated for deflection sensitivity with and without jet impingement to account for their temperature sensitivity. Microjets with velocity measured to be 40-65 m/sec produced deflections of 15-45 μm during jet impingement, corresponding to a thrust of 45-90 μN. When the majority of the liquid of the jet impinges on the cantilever to impart its total vertical momentum, measured thrust is within 10% of the value expected from simple fluid mechanics calculations. Figure 4 shows the cantilever directly in the jet flow at the point of maximum impingement force. Figure 5 depicts the measured thrust as the cantilever scans through the jet for various jet velocities (i.e. reservoir pressures).

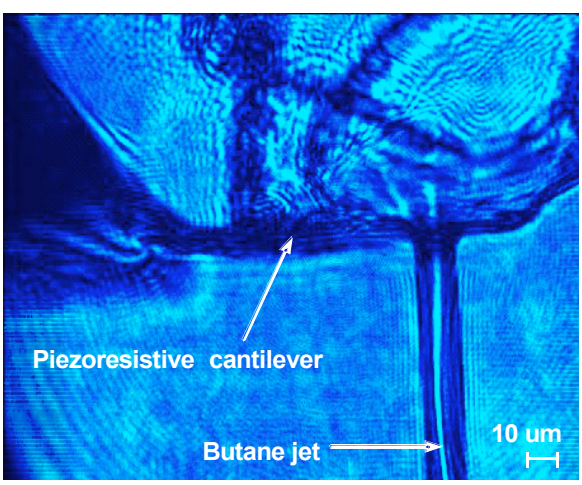

Fig. 4: *Jet hits the center of the piezoresistive cantilever. The vertical momentum of the liquid butane jet is fully transferred to the cantilever. The jet diameter and velocity are d=16 µm and v=27 m/s, respectively.*

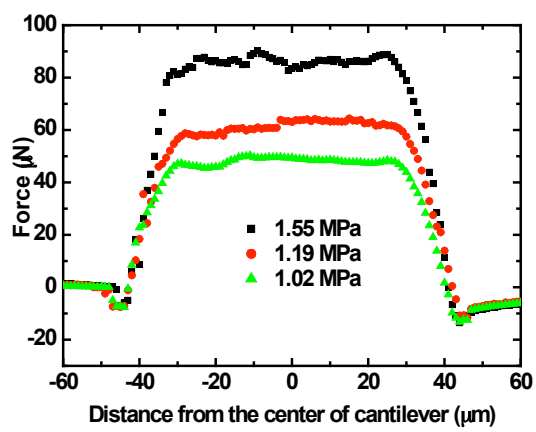

Fig. 5: *Thrust force (in units of µN) measured as a piezoresistive cantilever scans through a microjet at different jet pressures, i.e. jet velocities.*

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