# COTS MEMS Flow-Measurement Probes

**These relatively inexpensive probes are compact and have short response times.**

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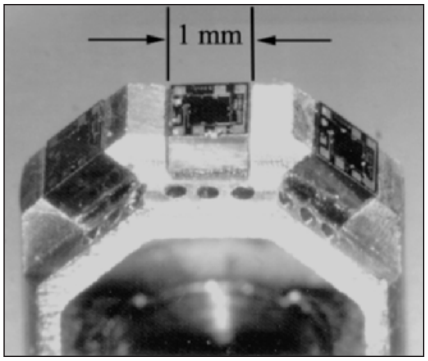
As an alternative to conventional tubing instrumentation for measuring airflow, designers and technicians at Glenn Research Center have been fabricating packaging components and assembling a set of unique probes that contain commercial off-the-shelf (COTS) microelectromechanical systems (MEMS) sensor chips. MEMS sensor chips offer some compelling advantages over standard macroscopic measurement devices. MEMS sensor technology has matured through mass production and use in the automotive and aircraft industries. At present, MEMS are the devices of choice for sensors in such applications as tire-pressure monitors, altimeters, pneumatic controls, cable leak detectors, and consumer appliances. Compactness, minimality of power demand, rugged construction, and moderate cost all contribute to making MEMS sensors attractive for instrumentation for future research.

Conventional macroscopic flow-measurement instrumentation includes tubes buried beneath the aerodynamic surfaces of wind-tunnel models or in wind-tunnel walls. Pressure is introduced at the opening of each such tube. The pressure must then travel along the tube before reaching a transducer that generates an electronic signal. The lengths of such tubes typically range from 20 ft (≈ 6 m) to hundreds of feet (of the order of 100 m). The propagation of pressure signals in the tubes damps the signals considerably and makes it necessary to delay measurements until after test rigs have reached steady-state operation. In contrast, a MEMS pressure sensor that generates electronic output can take readings continuously under dynamic conditions in nearly real time.




This **Probe Containing Three COTS MEMS Sensor Chips** is designed to measure flow angularity in a plane. A planned similar probe will contain five MEMS sensors for measuring flow angularity in three dimensions.

In order to use stainless-steel tubing for pressure measurements, it is necessary to clean many tubes, cut them to length, carefully install them, delicately deburr them, and splice them. A cluster of a few hundred 1/16-in.- (≈1.6-mm-) diameter tubes (such clusters are common in research testing facilities) can be several inches (of the order of 10 cm) in diameter and could weigh enough that two technicians are needed to handle it. Replacing hard tubing with electronic chips can eliminate much of the bulk. Each sensor would fit on the tip of a 1/16-in. tube with room to spare.

The Lucas NovaSensor P592 piezoresistive silicon pressure sensor was chosen for this project because of its cost, availability, and tolerance to extreme ambient conditions. The sensor chip is 1 mm square by 0.6 mm thick (about 0.039 by 0.039 by 0.024 in.) and includes 0.12-mm (≈0.005-in.) wire connection tabs.

The figure shows a flow-angularity probe that was built by use of three such MEMS chips. It is planned to demonstrate this MEMS probe as an alternative to a standard tube-type "Cobra" probe now used routinely in wind tunnels and aeronautical hardware. This MEMS probe could be translated across a flow field by use of a suitable actuator, so that its accuracy and the shortness of its response time could be exploited to obtain precise dynamic measurements of a sort that cannot be made by use of conventional tubing-based instrumentation.

*This work was done by Chip Redding, Floyd A. Smith, and Greg Blank of* **Glenn Research Center** *and Charles Cruzan of NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

*Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17243.*

# Measurement of an Evaporating Drop on a Reflective Substrate

**This system complements a prior one for measuring on a transparent substrate.**

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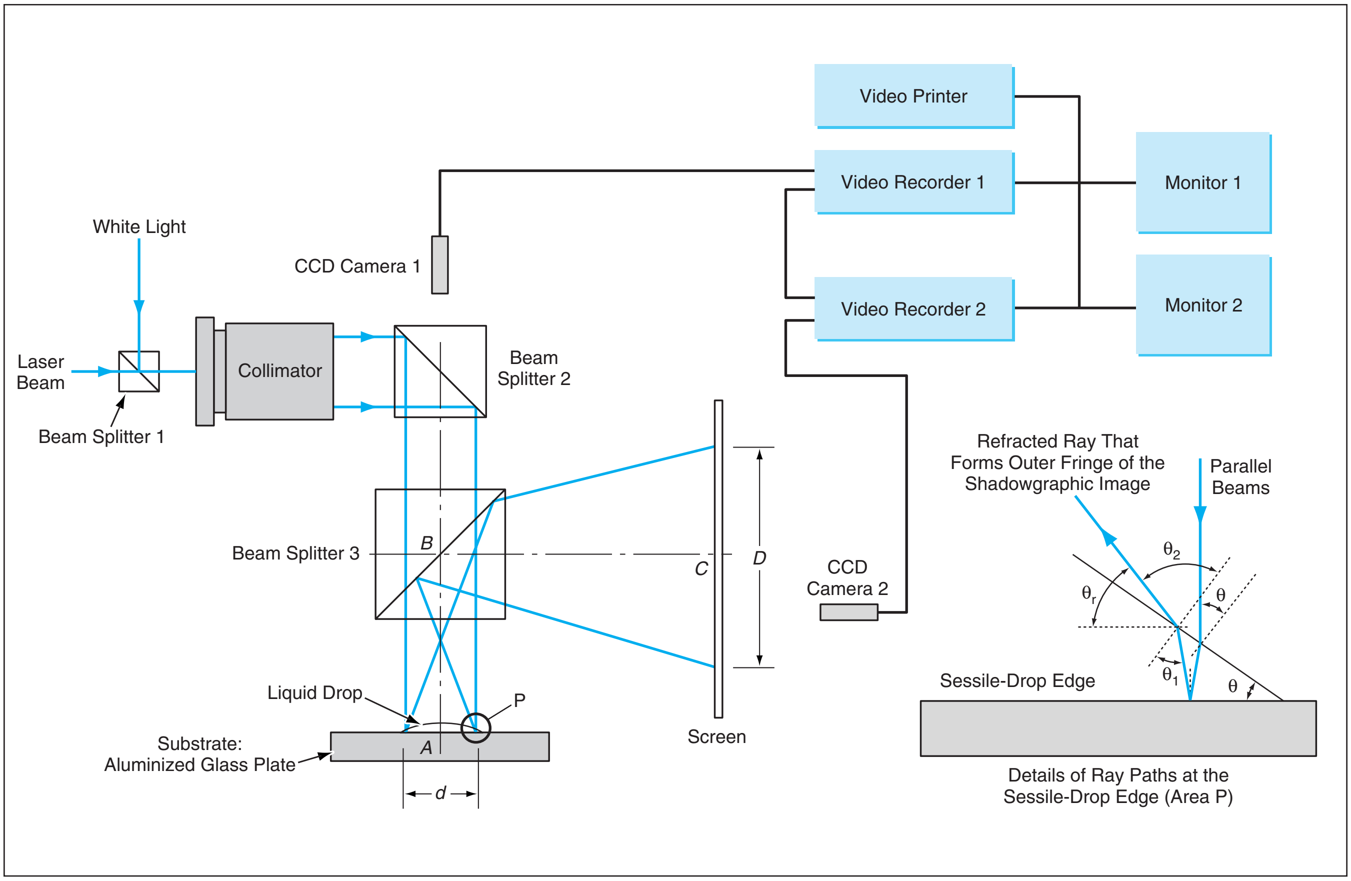
The figure depicts an apparatus that simultaneously records magnified ordinary top-view video images and laser-shadowgraph video images of a sessile drop on a flat, horizontal substrate that can be opaque or translucent and is at least partially specularly reflective. A similar apparatus for recording such images of a drop on a transparent substrate was described in "Measuring Contact Angles of a Sessile Drop and Imaging Convection Within It" (LEW-17075), *NASA Tech Briefs*, Vol. 25, No. 3 (March 2001), page 50. As in the case of the previously reported apparatus, the diameter, contact angle, and rate of evaporation of the drop as functions of time can be calculated from the apparent diameters of the drop in sequences of the images acquired at known time intervals, and the shadowgrams that contain flow patterns indicative of thermocapillary convection (if any) within the drop. These time-dependent parameters and flow patterns




The **Time-Dependent Diameters *d* and *D*** measured in images acquired by cameras 1 and 2 can be used to calculate the contact angle, volume, and other parameters of the drop on the substrate at point A.

are important for understanding the physical processes involved in the spreading and evaporation of drops.

The apparatus includes a source of white light and a laser (both omitted from the figure), which are used to form the ordinary image and the shadowgram, respectively. Charge-coupled-device (CCD) camera 1 (with zoom) acquires the ordinary video images, while CCD camera 2 acquires the shadowgrams. With respect to the portion of laser light specularly reflected from the substrate, the drop acts as a plano-convex lens, focusing the laser beam to a shadowgram on the projection screen in front of CCD camera 2.

The equations for calculating the diameter, contact angle, and rate of evaporation of the drop are readily derived on the basis of Snell's law of refraction and the geometry of the optics. The equations differ from those for the apparatus of the cited prior article. Omitting intermediate steps of the derivation for the sake of brevity, the results are the following:

The two related unknown quantities are the contact angle ($\theta$) and, for light that has been reflected from the substrate, the angle of refraction ($\theta_2$) of that light from the surface of the drop at a point near edge. These quantities are found by solving the simultaneous equations

$$\frac{2s}{(d+D)} = \frac{\cot\theta_2 + \tan\theta}{1 - \cot\theta_2 \tan\theta}$$

and

$$\sin\theta_2 = n\sin 2\theta\sqrt{1 - \frac{\sin^2\theta}{n^2}} - \cos 2\theta \sin\theta,$$

where $n$ is the index of refraction of the liquid in the drop, $s$ = the total length of paths AB and BC, $d$ is the apparent diameter of the drop as measured in the ordinary image acquired by CCD camera 1, and $D$ is the diameter of the shadowgraphic image acquired by CCD camera 2.

On the basis of a spherical-cap approximation of the shape of the drop, the thickness of the drop ($h$) at its apex is given by

$$h = \frac{d(1-\cos\theta)}{2\sin\theta}$$

and the volume ($\Omega$) of the drop is given by

$$\Omega = \pi h^2\left(\frac{d}{2\sin\theta} - \frac{h}{3}\right).$$

The time-average rate of evaporation of the drop, $W_{av}$, is considered to be an important parameter for quantifying evaporation strength and can be determined by

$$W_{av} = \frac{\Omega_0}{t_f},$$

where $\Omega_0$ is the initial volume of the drop and $t_f$ is the lifetime of the drop. The instantaneous rate of evaporation can be calculated by

$$W = \frac{\Delta\Omega}{\Delta t},$$

where $\Delta\Omega$ is the difference between the volumes of the drop at two measurement times separated by the interval $\Delta t$.

*This work was done by David F. Chao of* **Glenn Research Center** *and Nengli Zhang of Ohio Aerospace Institute. Further information is contained in a TSP (see page 1).*

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