

Hot Films on Ceramic Substrates for Measuring Skin Friction

Low-thermal-conductivity ceramic substrates, based on Space Shuttle tile technology, serve to increase sensitivity.

Dryden Flight Research Center, Edwards, California

Hot-film sensors, consisting of a metallic film on an electrically nonconductive substrate, have been used to measure skin friction as far back as 1931. A hot film is maintained at an elevated temperature relative to the local flow by passing an electrical current through it. The power required to maintain the specified temperature depends on the rate at which heat is transferred to the flow. The heat-

transfer rate correlates to the velocity gradient at the surface, and hence, with skin friction. The hot-film skin friction measurement method is most thoroughly developed for steady-state conditions, but additional issues arise under transient conditions.

Fabricating hot-film substrates using low-thermal-conductivity ceramics can offer advantages over traditional quartz or

polyester-film substrates. First, a low conductivity substrate increases the fraction of heat convected away by the fluid, thus increasing sensitivity to changes in flow conditions. Furthermore, the two-part, composite nature of the substrate allows the installation of thermocouple junctions just below the hot film, which can provide an estimate of the conduction heat loss.

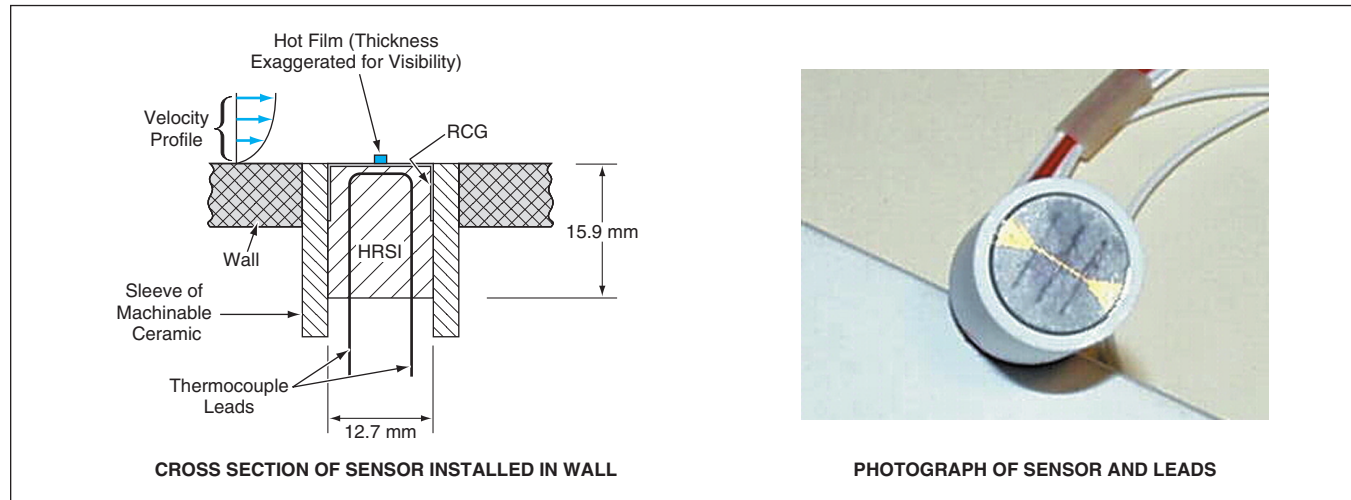


Figure 1. The Composite Ceramic Substrate of this hot-film sensor reduces conduction losses and increases sensitivity.

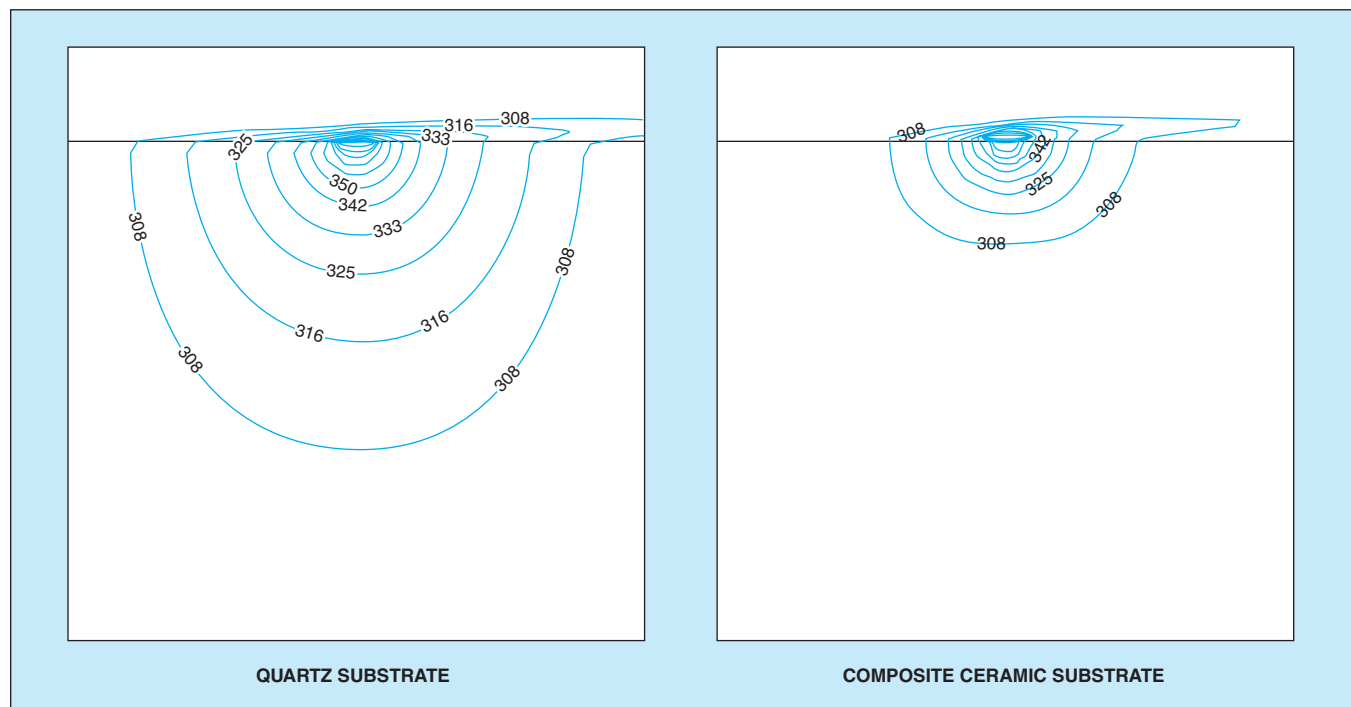


Figure 2. Steady-State Temperature Contours, determined from conjugate heat-transfer analyses, illustrate the effect of the lower thermal conductivity of the composite ceramic substrate relative to a quartz substrate. Temperatures are indicated in °C.

Figure 1 depicts a hot-film sensor of this type. The substrate is primarily composed of high-temperature reusable shuttle insulation (HRSI), a lightweight (density = 352 kg/m^3), porous, ceramic material originally developed to protect the space shuttle from aerodynamic heating. A hard, non-porous coat of reaction-cured glass (RCG) extends over the face of the cylinder and about one-third of the way down the side providing a surface on which the metallic hot film and its leads can be deposited. Small-diameter [0.005 in. (0.127 mm)] thermocouple wires are routed through the HRSI. Small grooves in the end of the HRSI cylinder, form the lands of the thermocouples and are deep enough such that the wires lie flush with the HRSI surface prior to being coated with the RCG. The three thermocouple junctions are placed in a line. The substrates are placed in a machinable-cer-

amic sleeve that provides electrical isolation for the hot-film leads. Type R thermocouples must be used because the high firing temperature of the RCG coating precludes the use of the more-sensitive thermocouples of type K's.

The hot film itself is approximately 0.004 in. ($\approx 0.102 \text{ mm}$) wide and 1/4 in. (6.35 mm) long. Fabrication of the hot film and its leads begins with hand painting the desired pattern using organometallic inks. The painted substrate is then heated in an oven, which removes the solvents from the ink leaving only a gold-alloy film (see Figure 1 photo). The sensor thermocouples provide feedback control to the oven. These techniques could be used for the fabrication of other temperature and heat-flux gauges on high-temperature ceramics.

Conjugate heat-transfer analyses were performed on different substrate mate-

rials in air at moderate velocity gradients ($7,500 \text{ s}^{-1}$). For the composite ceramic substrate, the ratio of heat leaving the sensor via convection to total heat produced is about 4 times higher than for a quartz substrate. Figure 2 depicts steady-state temperature contours for quartz and a composite ceramic substrate. Preliminary bench tests comparing hot films on composite ceramic and machinable-ceramic substrates indicate that, at overheat ratios of 1.2 and in horizontal orientations, the higher conductivity machinable-ceramic substrates require over 2.5 times the power.

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Probe Without Moving Parts Measures Flow Angle

Flow angle is computed from forces measured by use of strain gauges.

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The measurement of local flow angle is critical in many fluid-dynamic applications, including the aerodynamic flight testing of new aircraft and flight systems. Flight researchers at NASA Dryden Flight Research Center have recently developed, flight-tested, and patented the force-based flow-angle probe (FLAP), a novel, force-based instrument for the measurement of local flow direction. Containing no moving parts, the FLAP may provide greater simplicity, improved accuracy, and increased measurement access, relative to conventional moving-vane-type flow-angle probes.

Forces in the FLAP can be measured by various techniques, including those that involve conventional strain gauges (based on electrical resistance) and those that involve more advanced strain gauges (based on optical fibers). A correlation is used to convert force-measurement data to the local flow angle. The use of fiber optics will enable the construction of a miniature FLAP, leading to the possibility of flow measurement in very small or confined regions. This may also enable the "tufting" of a surface with miniature FLAPs, capable of quantitative flow-angle measurements, similar to attaching yarn tufts for qualitative measurements.

The prototype FLAP was a small, aerodynamically shaped, low-aspect-

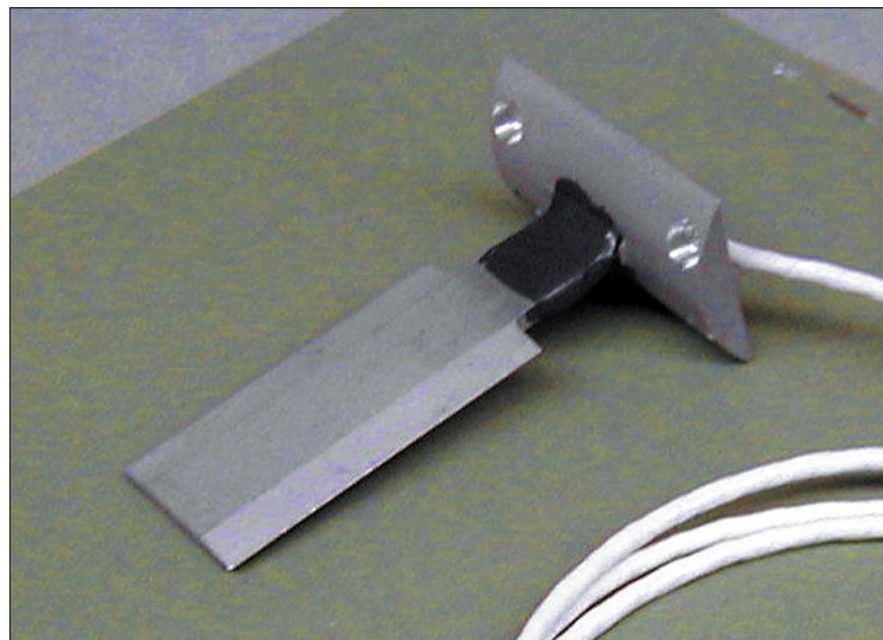


Figure 1. The **Prototype FLAP** was a fin instrumented with simple electrical-resistance strain gauges.

ratio fin about 2 in. ($\approx 5 \text{ cm}$) long, 1 in. ($\approx 2.5 \text{ cm}$) wide, and 0.125 in. ($\approx 0.3 \text{ cm}$) thick (see Figure 1). The prototype FLAP included simple electrical-resistance strain gauges for measuring forces. Four strain gauges were mounted on the FLAP; two on the upper surface and two on the lower surface. The gauges were connected to

form a full Wheatstone bridge, configured as a bending bridge.

In preparation for a flight test, the prototype FLAP was mounted on the air-data boom of a flight-test fixture (FTF) on the NASA Dryden F-15B flight research airplane. The FTF is an aerodynamic fixture for flight-research experiments that is carried underneath the