of constant reflected-shock pressure. The results show that monitoring the 2.0 μ band radiation from small amounts of $CO_2$ in the test gas can be used to indicate usable test times in shock tunnels. Such indicated test times are in good agreement with the predictions of Davies' shock bifurcation model.

### References


[1] Davies, L. and Wilson, J. L., "The Influence of Shock and Boundary Layer Interaction on Shock Tube Flows," A.R.C. 29 064-Hyp. 615, May 1967, National Physical Lab., Teddington, England.

[2] Lapworth, K. C., *The High Temperature Aspects of Hypersonic Flow*, AGARDograph 68, Pergamon, N.Y., 1964, pp. 255–267.

[3] Richmond, J. K. and Parson, R. J., "Driver Gas Contamination in Shock Tunnels," D1-82-0806, Dec. 1968, Boeing Scientific Research Labs., Seattle, Wash.

[4] Bull, D. C. and Edwards, D. H., "An Investigation of the Reflected Shock Interaction Process in a Shock Tube," *AIAA Journal*, Vol. 6, No. 8, Aug. 1968, pp. 1549–1555.

[5] Markstein, G. H., "Flow Disturbances Induced Near a Slightly Wavy Contact Surface, or Flame Front, Traversed by a Shock Wave," *Journal of the Aerospace Sciences*, Vol. 238, No. 3 March 1958, pp. 238–239.

[6] Echigo, R., "Evaluation of Band Emissivities of Carbon Dioxide and Water Vapour," *JSME Bulletin*, Vol. 10, Aug. 1967, pp. 671–679.


# Mass Flow Rate Measurements in a Heterogeneous Medium


R. F. Davey*

*California Institute of Technology, Pasadena, Calif.*


### Nomenclature

$A,B$ = calibration constants
$d$ = hot wire diameter
$e$ = voltage across hot wire
$k$ = thermal conductivity
$L$ = hot wire length
$Nu$ = Nusselt number = $e^2/r_w \pi L k \Delta T$
$r_w$ = hot wire resistance
$Re$ = Reynolds number = $\rho_f u d/\mu_f$
$u$ = gas velocity
$\Delta T$ = hot wire overheat

***Subscript***

$f$ = value of parameter at the film temperature: $T_f = T + \frac{1}{2}\Delta T$

### 1. Introduction

An experimental study of the effect of a density gradient on the stability of a separated boundary layer led to the development of a new technique for measuring the mass flow rate in a nonuniform medium.[1] The small size of the experimental apparatus (the boundary-layer thickness was about 1 mm at the separation point) and the need to measure flow fluctuations made the sensor requirements particularly stringent. In fact, adequate spatial resolution and time response could be achieved only with a hot wire oriented spanwise to the two-dimensional flow.

Although hot wires have been used with great success for measuring the temperature and velocity of homogeneous flows, a single hot wire is, in general, unusable in a heterogeneous medium because the signal produced varies with changes in fluid properties (e.g., thermal conductivity, viscosity) as well as with changes in the flow parameters one wishes to measure. Following an analysis by Corrsin,[2] several investigators have used sensors with two or more hot wires, relying upon differences in overheat, length and wire diameter to obtain different sensitivities to composition and velocity. Although some success has been reported recently by Way and Libby[3] using two wires and mixing the signals to obtain simultaneous velocity and density measurements, their probes require crossed sensors and, therefore, lack the spatial resolution required for the present application.

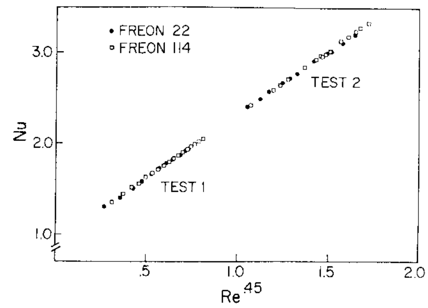


**Fig. 1 Calibration of hot wires in Freon 22 and Freon 114.**

### 2. Analysis

The relationship governing the use of hot wires in fluid flows is King's law, usually expressed as: $Nu = A + BRe^n$. Collis and Williams[4] gave a value of 0.45 for the power law exponent $n$ in the range of Reynolds numbers used in the shear layer experiments. This value was verified by the calibration experiments discussed below.

If the hot wire equation is rewritten to represent a particular sensor operating at a fixed overheat, the overheat and all the parameters describing the hot wire can be included in the calibration constants, leaving

$$e^2 = A^*k + B^*(k/\mu_f^n)(\rho u)^n$$

It can be seen from this equation that if two gases could be found with equal thermal conductivities and viscosities, a single hot wire could be used to provide a measurement of mass flow rate in all mixtures of the gases. Since the shear layer experiments sought to determine the effect of a density gradient, a large difference in molecular weight was also desired. In general, these requirements are incompatible since the thermal conductivity usually decreases with increasing molecular weight. However, two Freons were found with a density ratio of 1.98 which nearly satisfied the requirements. Their properties are summarized in Table 1.

### 3. Experimental Evaluation

Several calibration experiments were performed to verify the theoretical predictions. In every case, measurements taken in the two Freons fell on a single calibration line, as predicted theoretically. The hot wires used were 90% platinum, 10% rhodium, with a diameter of 0.0001 in. and a length of 1 mm. They were heated using constant temperature bridge circuits to an overheat of about 300°C. This brought the resistance to 1.5 times the ambient temperature

**Table 1 Properties of Freon 22 and Freon 114**

| Property | Freon 22 | Freon 114 | Ratio: 114/22 |
|---|---|---|---|
| Molecular weight | 86.48 | 170.93 | 1.976 |
| $k$ (joule/m-sec °K) | 0.01172 | 0.01119 | 0.954 |
| $\mu_f$ (poise) | $1.59 \times 10^{-4}$ | $1.40 \times 10^{-4}$ | 0.881 |
| $k/\mu_f^{0.45}$ | | | 0.991 |


Received April 28, 1971. This work was supported by the Office of Naval Research.


* Associate Research Engineer.

value. The results of two of the calibration tests are shown in Fig. 1. The first test was conducted with the pressure at 7 psia whereas the second test was conducted at atmospheric pressure.

Although the results were positive and the technique was considered usable, it should be noted that a certain inherent uncertainty remains in the mass flow rate measurements because of the small differences in the thermal conductivities and viscosities. . Given a particular signal voltage, the error introduced by the difference between the corresponding mass flow rates for pure Freon 22 and pure Freon 114 increases from about $\pm 1.6\%$ at the lowest Reynolds number measurements to as much as $\pm 4\%$ with $Re \simeq 2$.


### References

[1] Davey, R., "An Experimental Investigation of the Effect of a Density Gradient on Shear Layer Instability," Ph.D. thesis, March 1971, California Inst. of Technology, Pasadena, Calif.

[2] Corrsin, S., "Extended Applications of the Hot-Wire Anemometer," TN 1864, April 1949, NACA.

[3] Way, J. and Libby, P., "Hot-Wire Probes for Measuring Velocity and Concentrations in Helium-Air Mixtures," *AIAA Journal*, Vol. 8, No. 5, May 1970, pp. 976–978.

[4] Collins, D. and Williams, M., "Two-Dimensional Convection from Heated Wires at Low Reynolds Numbers," *Journal of Fluid Mechanics*, Vol. 6, No. 3, Oct. 1959, pp. 357–384.


# Hypersonic Lee-Surface Heating Alleviation on Delta Wing by Apex-Drooping


DHANVADA MADHAVA RAO*
*NASA Langley Research Center, Hampton, Va.*


In a recent Note,[1] Whitehead reported high heating rates on the leeward meridian of a 75° swent delta wing at 5° incidence in $M = 6$ flow. This peak heating was originally thought to be associated with flow impingement induced by free vortices following separation from the sharp leading-edges (Fig. 1a). Subsequently, a detailed study was made of a number of lee-surface oil-flow patterns obtained in tests representative of conditions where Ref. 1 had shown the first peak in leeward heating to be most pronounced. It was found that the flow remained attached over the apex region and was initially vortex-free, the "feather" pattern characteristic of a vortex system appearing only at some distance downstream of the apex (Fig. 2 shows a typical pattern). This observation led to the conjecture that the vortices in question originate within the laminar boundary layer as a result of three-dimensional flow development in the apex region (Fig. 1b). If so, by preventing vortex formation in this region, a vortex-free flow over the entire wing should result. Since such a vortex system has not been observed on delta wings at zero incidence, drooping the apex portion of the wing to locally align it with the freestream could be a possible means of vortex suppression. This reasoning formed the basis of a brief experimental investigation with a 75° delta wing at 5° incidence in the 11-in. Hypersonic ($M = 6.8$) Blowdown Tunnel at NASA Langley Research Center, at a unit Reynolds number of 0.2 million/in. (model length Reynolds number of 2 million).

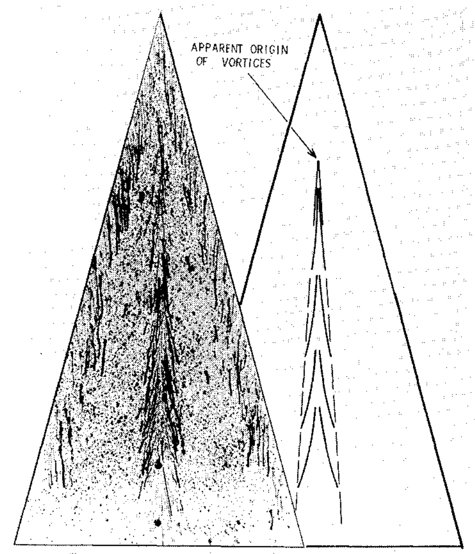


**Fig. 2 Oil flow picture showing origin of vortices on lee-surface at 5° incidence (Reynolds number 0.2 million/in.).**

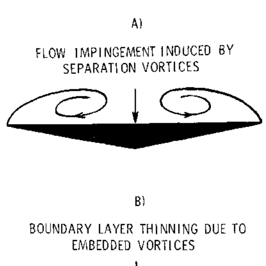


**Fig. 1 Vortex flow on lee-surface of delta wing.**

Received May 3, 1971.

* Resident Research Associate, Configuration Flow Fields Section, Hypersonic Vehicles Division; on leave from National Aeronautical Laboratory, Bangalore, India. Member AIAA.

Preliminary oil-flow tests showed that apex-drooping successfully eliminated the high shear and vortex-associated feather pattern found on the delta wing without droop. In order to confirm the beneficial effect of vortex suppression on the centerline heating, experiments on a heat-transfer model using the phase-change paint method were carried out. In this method,[2] the model is coated with a paint of known melting point and then exposed to the tunnel flow; the time increment to reach the melting temperature at a given model location measures the local heat-transfer rate.

The heat-transfer model, incorporating a silicone-rubber insert over a substantial portion of the upper surface to reduce heat conduction, was first tested in the flat condition (i.e., without droop), and then with the apex bent down approximately along a circular arc through 5° slope, as indicated in Fig. 3. A temperature-sensitive paint with a melting point of 103°F, the lowest available, was applied to the rubber surface. During the tests, the model was photographed with a 35-mm time lapse camera at 10 frames/sec.

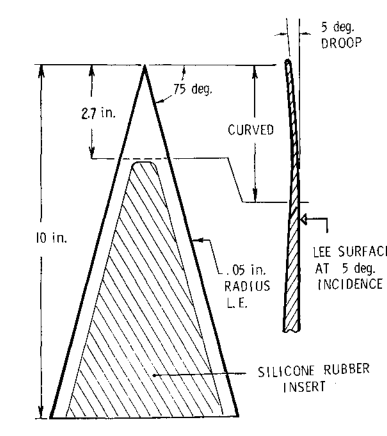


**Fig. 3 Delta-wing heat-transfer model geometry.**