flows offer no proof of the general equivalence of this supersaturated flow to a subsaturated flow. Equivalence is shown here for the hypersonic viscous induced pressures on a flat plate. Equivalence must, at present, be assumed for general application of supersaturation to broaden the test regime of a given tunnel.

In conclusion: 1) the amount of supersaturation that can be achieved at high Mach numbers with air can also be obtained using nitrogen as the test gas, and 2) the flat plate proves to be a very useful tool in condensation studies.

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A Thin-Film Radiative Heat-Transfer Gage

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In order to measure the total integrated radiative heat flux due to shock-layer radiative emission on aerodynamic configurations mounted in high-enthalpy, supersonic, shock-tube generated flows, a fast response thin-film total radiation heat-transfer gage has been developed at The Ohio State University Aerodynamic Laboratory. Standard thin-film resistance thermometer techniques have been applied in this gage because the use of such techniques in convective heating measurements in impulse devices is well understood and quite extensively documented in the literature.[1, 2]

A schematic of the thin-film radiative heat-transfer gage is shown in Fig. 1. It consists of a double-layer thin-film sensing element mounted on a Pyrex backing material. The bottom layer of the double-layer sensing element is a thin film of Bright Platinum no. 05-X, whereas the top layer is a thin film of Luster Black no. 4771. Both of these materials are liquid metal suspensions marketed by the Hanovia Liquid Gold Division, Engelhard Industries, East Newark, N. J. The Bright Platinum material is an electrical conductor and serves as the resistive element in the d.c.-powered, constant current circuit designed to measure the variation in the gage resistance. The Luster Black material is for all practical purposes nonelectrically conducting; however, it has a high absorptivity at wavelengths below 1 μ and thus provides the proper gage surface characteristics for re-entry heating investigations of current interest. The percent transmission and reflection of a Luster Black thin-film surface[3] is shown in Fig. 2, and it can be seen that, in the wavelength region below 1 μ, the absorptivity will be approximately 0.8. The

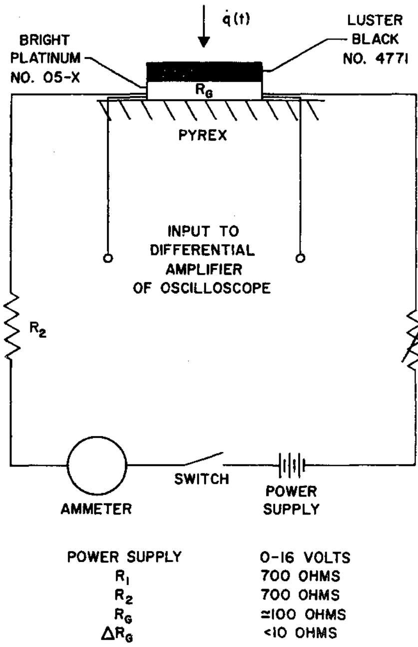

Fig. 1 Schematic of thin-film gage and electrical circuit.

lower spectral absorptivity of the Luster Black in the infrared is associated with its high transmissivity in this wavelength region. However, because of the low transmissivity of the Bright Platinum no. 05-X thin film, the absorptivity of the double-layer thin-film gage is actually much higher in the infrared than indicated by the surface characteristics shown in Fig. 2.

It should be noted that the exact spectral characteristics of thin films depend on the thickness and uniformity of the film, and therefore the spectral characteristics of different thin-film heat-transfer gages will vary somewhat. However, such variations have a small effect on the absorptivity of gages of the present type. For example, an obviously extreme deviation of 50% in the reflectivity of the Luster Black thin film from that shown in Fig. 2 produces only about a 12% change in the gage absorptivity. It would thus appear that variations in gage surface characteristics will be small and can be neglected. This negligible difference between surface characteristics of different gages was borne out in a recent investigation of stagnation-point radiative heat transfer in which three different thin-film gages of the forementioned type were used to measure radiation heat transfer[4] over a wide range of flow conditions. Analysis of the results of this investigation showed any differences in surface spectral characteristics to have an indiscernible effect.

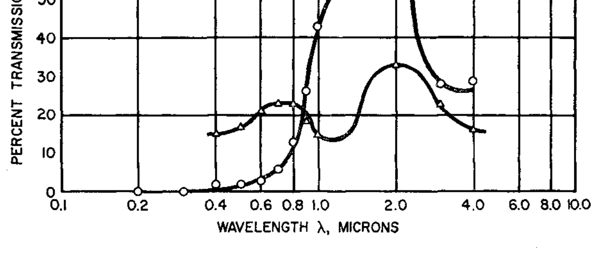

Fig. 2 Transmission and reflection characteristics of Luster Black no. 4771.

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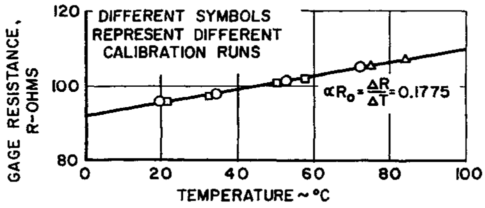
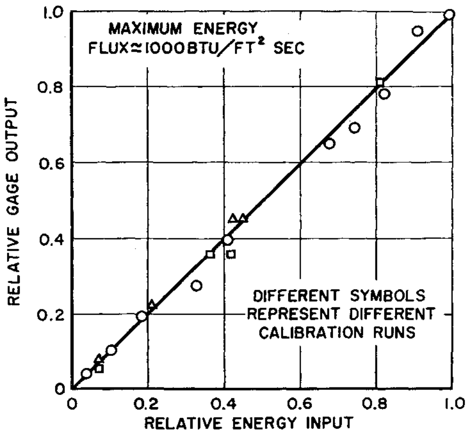


a) TYPICAL THIN FILM GAGE STATIC CALIBRATION



b) THIN FILM GAGE OUTPUT FOR VARYING ENERGY INPUTS

Fig. 3 Calibration results for thin-film gage.

The electrical circuit, of which this gage is a part and as is shown in Fig. 1, is designed to measure the time history of the voltage drop across the gage ΔE. For a constant heat flux $\dot{q}$, which is applied at time $t = 0$, the heat-transfer rate may be expressed in terms of ΔE and the time length of exposure to the heat flux t through the relation[1, 2]

$$\dot{q} = \tfrac{1}{2}(\pi\beta_m)^{1/2}(1/I\alpha R_0)(\Delta E/t^{1/2}) \tag{1}$$

where $\alpha R_0 = \Delta R/\Delta T$ is a property of the sensing element, which is a constant, and I is the gage current, which is kept constant during each test. β_m is a property of the backing material. For cases where the heat flux is not constant with time, a more general relationship between heat-transfer rate and gage output must be used.[1, 2]

In the measurements performed at The Ohio State University, the value[5] of $\beta_m^{1/2}$ has been taken to be 0.0743 Btu/ft^2-sec$^{1/2}$°F, and a correction for variable backing material thermal properties has been applied using the results of Ref. 6. αR_0 is determined from static calibrations in the laboratory for each gage. The results of such a calibration for a typical gage are shown in Fig. 3a where the different symbols correspond to different calibration runs.

The thin-film radiative heat-transfer gages constructed at The Ohio State University have also been checked dynamically using a Xenon flash lamp to provide a pulse of radiation. These pulses, as determined with a 1P22 photomultiplier, have a rise time of 4 μsec, and the heat flux remains relatively constant for 20–25 μsec. The purpose of these dynamic tests was to provide a check on the linearity of the gage. In Fig. 3b the results of several such dynamic calibrations are presented in terms of the relative gage output as a function of the relative energy input. The maximum energy flux during these tests was 1000 Btu/ft^2/sec and it can be seen that, over the range of the calibration results, the gage output is linear.

It should be noted that the thickness of the sensing element of the present thin-film gage is approximately 0.1 μ, and any effect resulting from the finite thermal capacity of the sensing element would be expected to be negligible. This has been borne out by the results obtained from the dynamic calibration tests.

In order to sense only radiative fluxes using the thin-film gage described here, it is necessary to shield the gage from convective heating inputs. This is done by positioning the gage within the model being tested and behind a transparent window that is flush-mounted on the model surface. Thus, in analyzing the results obtained through the use of this double-layer thin-film radiative heat-transfer gage, consideration must be given to not only the absorption characteristics of the surface of the sensing element, but also to the transmission characteristics of the window behind which the gage is positioned and to the geometrical view factor that relates the model surface radiative heat-transfer rate to the average heat-transfer rate at the surface of the recessed gage. For all measurements performed to date at The Ohio State University Aerodynamic Laboratory, synthetic sapphire windows have been used. The transmission characteristics of sapphire are well known and may be found in Refs. 7–9. For sapphire windows 0.020 in. thick, the wavelength region of transmission is from 0.17 to approximately 6 μ. The view factor for a given model and gage configuration can be derived from purely geometric considerations if the gas sample being viewed can be assumed to have uniform properties and to be optically thin. This is carried out in Ref. 10 for the stagnation point of a hemispherical nose configuration.

Commercially available liquid-metal suspensions have been used in the development and construction of the radiative heat-transfer gage described here because, with their use, thin films may be deposited with ease. In constructing this gage, the two thin films that make up the double-layer sensing element are applied individually through the use of the manufacturer's recommended procedure.

Extensive measurements have been obtained using the double-layer thin-film radiative heat-transfer gage described here, and these results are reported in Refs. 4 and 10. Earlier measurements were obtained using a similar thin-film gage that had a sensing element made of Bright Gold EF no. 31-A, a liquid-metal suspension that is also manufactured by the Hanovia Liquid Gold Division. These earlier measurements, which were reported in Ref. 11, are in good agreement with the later results obtained using the double-layer thin-film gage. The advantage of the double-layer thin-film gage as compared to the Bright Gold gage is that it is sensitive to radiation over a much wider wavelength region. The good agreement that exists between these measurements does serve as a partial verification of the techniques discussed here.

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An Investigation of Cylindrical Starting Flows

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When a large pressure discontinuity is suddenly applied across a two-dimensional orifice or slit, a nonsteady flow is created which later develops into a steady, rapid expansion. An experimental program was undertaken to study this expansion and evaluate it as a possible means of generating electronic population inversions.[1] A by-product of this study was a brief investigation of the early stages of the flow, when it is dominated by a cylindrical blast wave. The latter work is reported here. The results were presented in abbreviated form in Ref. 2.

The orifice, which was 2 mm high and approximately 3 in. wide, was cut in the end wall of a shock tube, so that the configuration was essentially that of a shock tunnel with a nozzle of semiangle $\simeq 90°$. Qualitative studies of the flow were made using schlieren photography. An example is shown in Fig. 1. The gas (air) is shown flowing through the orifice from left to right, and the flow is bounded by a strong cylindrical shock traveling outward into the low-pressure region. Other flow details that are indicated are an inner shock wave typical of an overexpanded nozzle flow and the two separated flow regions. The latter feature a mixing zone and an oblique shock wave caused by the separation. The interface separating gas initially upstream of the orifice from that downstream

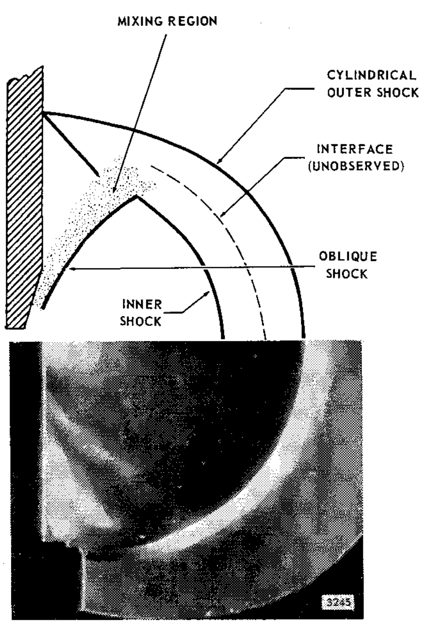

Fig. 1 Orifice starting flow.

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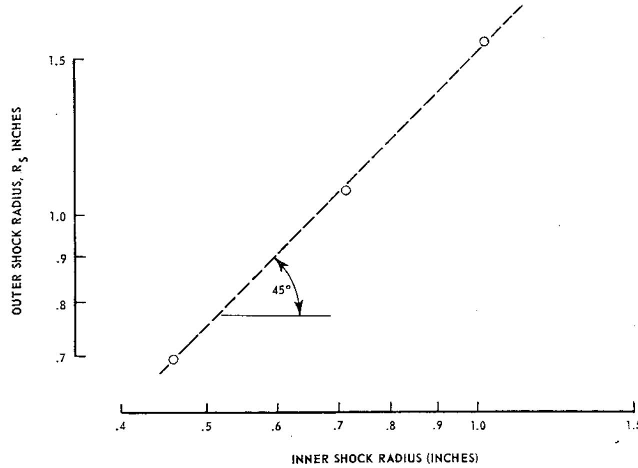

Fig. 2 Flow scaling.

is indicated, although it was not observed experimentally. The edge of the orifice is shown to be beveled, and, although the expansion angle is very large (~80°), the flow tended to follow the surface. Photographs taken with an unbeveled orifice plate did not show this feature; separation occurred at the orifice edge. It should be stressed that these observations were for flows for which the separation angle was less than 80°. For the photomultiplier studies described below, the unbeveled configuration was always used.

The schlieren photographs revealed an interesting and important feature of the flow. That is, for fixed conditions, photographs taken at different times were scaled replicas of each other. This is demonstrated in Fig. 2, which shows the radius of the outer shock plotted against that of the inner shock, both being measured along the centerline. Over the range indicated (a doubling of the shock radii), the proportionality is very good. On the basis of this evidence, one might expect that the major portion of the flow field is self-similar. Thus, explicit time dependence can be eliminated from the description of the flow by referring all radial distances to the outer shock radius. This point is discussed later. Photographs taken under different conditions did not scale; this is also considered later.

Complementing the study described previously was a quantitative investigation of the growth of the outer shock. At early times this shock is strong, and immediately behind it the processed gas is radiating, permitting the use of photomultipliers as time-of-arrival gages. One of these, receiving collimated light from the edge of the orifice, recorded the emergence of the flow. A second one, receiving light from a known distance downstream, recorded the arrival there. The outputs were displayed on a dual-beam oscilloscope, a record being shown in Fig. 3. The signal preceding the arrival at the downstream station is due to scattered light.

Before any results are presented, consider now a mathematical description of the situation based on two-dimensional

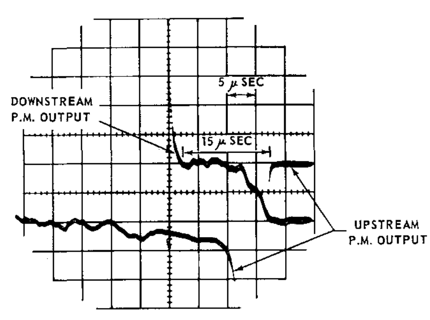

Fig. 3 Typical oscilloscope record.