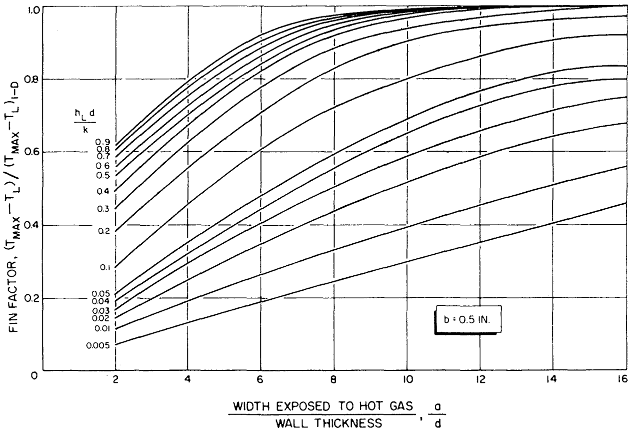

Fig. 2 Comparison of one- and two-dimensional heat transfers

Table 1 Comparison of three methods for computing maximum wall temperature of sample problem; Q/A = 20.0 Btu/in²-sec

	Q/A, Btu/in.²-sec Gas side	Liquid side	T_{max}, °F	$T_{max}/T_{max\ numerical}$
One-dimensional	20.4	20.4	1929	2.2
Infinite series	20.4	...	758	0.8
Numerical	20.1	9.8	914	1.0

closer agreement with the numerical results than with the temperature obtained by neglecting the heat that flows into the coolant through the sides of the tubes.

Nomenclature

- a = width of tube subjected to a heat flux
- b = height of tube
- d = tube wall thickness
- h_L = coolant-side heat transfer coefficient
- h_G = gas-side heat transfer coefficient
- k = tube thermal conductivity
- Q/A = heat flux
- T_L = bulk temperature of coolant
- T_G = adiabatic wall temperature of gas
- T_{max} = maximum tube wall temperature
- 1-D = one-dimensional

Schlieren Photography of Projectile Wakes Using Resonance Radiation[1]

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The use of resonance radiation to increase schlieren sensitivity by many orders of magnitude beyond current technique is discussed. An experimental study using sodium vapor and light near 5896 Å produced high quality schlieren photographs of projectile wakes at densities less than 1% of atmospheric.

IN ATTEMPTING to study transiton from laminar to turbulent flow in the wakes of high speed projectiles, it has been found necessary to reduce the gas density to only a few percent of atmospheric density, a level close to the limit of sensitivity of schlieren (1)[4] technique. Under these conditions, in a set of schlieren photographs of decreasing pressure, it is exceedingly difficult to determine whether the disappearance of the characteristic pattern of small scale turbulence in wakes is due to laminar flow or to loss of sensitivity. The present work was undertaken in an attempt to remove this ambiguity by achieving at least an order of magnitude improvement in sensitivity.

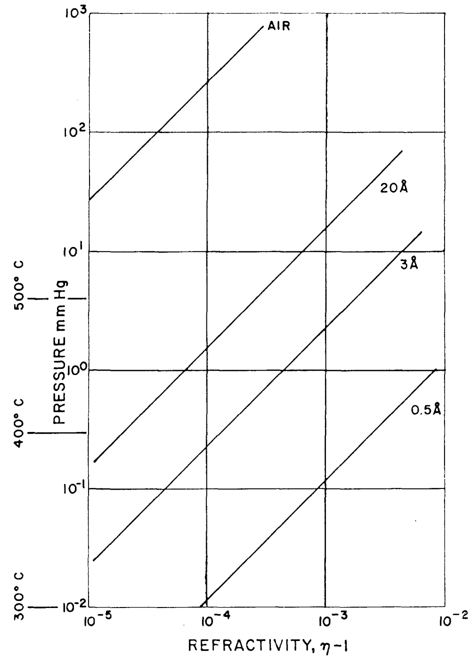

Fig. 1 Refractivity as a function of pressure for sodium vapor illuminated by light 0.5, 3, and 20 Å from resonance. A line for air, illuminated by visible light, is also drawn. Temperatures are those required to produce corresponding equilibrium vapor pressures of sodium

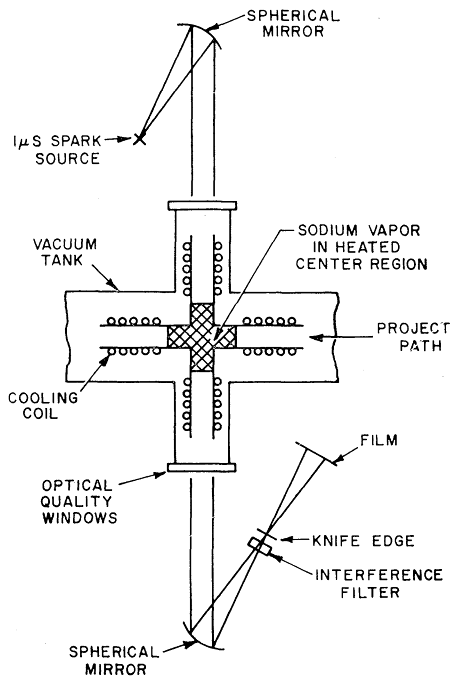

Fig. 2 Apparatus used to produce partial pressures of sodium in working fluid of schlieren system

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[4] Numbers in parentheses indicate References at end of paper.

At the time the work was begun, it was felt that refinement of the optics had already been pushed to the point of diminishing returns. Another independent factor affecting sensitivity is the refractivity of the working fluid, to which the sensitivity of a schlieren system is directly proportional. Calculations using the well-known dispersion formula of classical radiation theory (2) show that the absolute value of refractivity of a gas close to a resonance line can be many orders of magnitude larger than that of air in the visible portion of the spectrum far from its resonances in the vacuum ultraviolet. It was therefore decided to explore the possibility of enhancing the refractivity of the working fluid by using radiation close to a resonant transition.

Since the technical difficulties associated with working in the vacuum ultraviolet are very substantial, it appeared more attractive to attempt enhancement of the refractivity by using a gas with strong resonances in the ultraviolet or visible region. Several possibilities were considered, including potassium in the infrared and mercury in the quartz ultraviolet. However, sodium vapor with its strong resonance lines near 5896 Å seemed the most convenient choice for an initial experimental study. The radiation is in the visible so that standard light sources and schlieren instrumentation can be used, and appropriate narrow band filters are readily available.

The absolute value of the refractivity of sodium (3) as a function of pressure for various wavelengths close to its resonance lines is compared with that of air in Fig. 1. It can be seen, for example, that if a system uses light at 20 Å from resonance, a refractivity is obtained with sodium vapor which is more than two orders of magnitude larger than is obtained with air at the same pressure. With light 0.5 Å from resonance, the gain is seen to be four orders of magnitude.

A schematic of the apparatus used in the present work is shown in Fig. 2. The optical system is the usual schlieren off-axis paraboloidal mirror arrangement with the exception of a narrow band interference filter placed just in front of the knife edge. The remainder of the apparatus consists of a vacuum tank through which projectiles may be fired and an oven consisting of two 30-in. lengths of 2-in. diam pipe in the form of a cross. The central 6 in. of the cross can be heated to temperatures of 500° C. The arms of the cross are water cooled.

Sodium is placed in the center of the cross, and the total pressure is fixed with the working fluid. When heat is applied, a partial pressure of sodium is established in the central region. Under steady-state operation, evaporation at the liquid metal surface and condensation in the cooled regions take place continuously, the liquid condensate returning by gravity flow from the arms to the center. Since the steady-state diffusion equation does not contain the diffusion coefficient, the sodium vapor density distribution depends only on the temperature distribution of the walls of the cross and is essentially the same over a wide range of total pressures.

The absolute vapor density was determined as a function of wall temperature by measuring the percent transmission through the vapor of light which had been selected by an interference filter and comparing with similar test cell (4) transmission calibrations. The sodium level reached in the central region was very close to the equilibrium vapor pressure for the measured wall temperature.

Preliminary studies with sodium vapor, using a monochromator in conjunction with a sandwich type of spark-gap light source, showed a reversal of the light and dark portions in schlieren photographs as the wavelength region transmitted was changed from slightly less than resonance to slightly greater than resonance. This verified that the refractivity changes sign and is negative at wavelengths shorter than resonance. These results also showed that a light source asymmetric about the resonance line is required in order to maximize the effect. Two interference filters were used in the present investigation: one, 70-Å wide with the peak transmission 20 Å from the resonance lines and toward the red; the other 20-Å wide with the peak transmission 6 Å from the resonance lines and also toward the red.

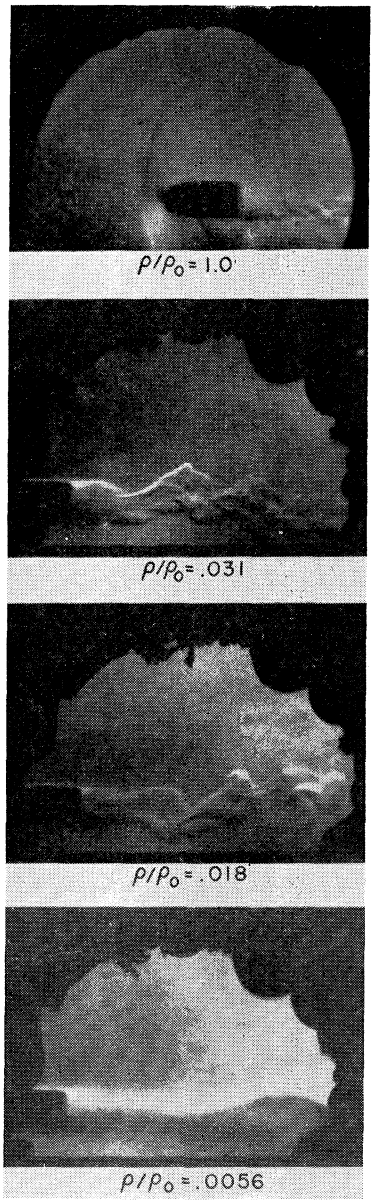

Fig. 3 Schlieren photographs of 0.22-cal rifle bullets. Velocity is 1200 fps; exposure time is 1μ sec. Top photograph is in air; bottom three photographs are in argon containing 3 mm Hg of sodium vapor and are subsonic. All four photographs were taken with the same optical system (knife edge cutoff)

Fig. 3 shows four wake photographs taken using the wide band filter and an exposure of 1 μsec. The first photograph is in air at 1 atm pressure and room temperature. This photograph indicates the capability of the optical system. The last three photographs, taken with the same optical system, are in argon with an oven temperature of 500°C and a sodium vapor pressure of 3 mm Hg. The total pressures were 50, 30, and 10 mm Hg, and the corresponding densities were 3.1, 1.8, and 0.56% of atmospheric. Photographs taken at these densities without sodium vapor show no wake structure. Although it is the intention of this note primarily to report the resonance technique, the authors would like to point out that the regular pattern of eddies shown in Fig. 3 gives strong support to the recent hypothesis of Goldburg and Fay (5) that transition to unsteady motion in the compressible wake is the same vortex shedding process as in the incompressible case.

The results of this study show that the use of resonance radiation makes it possible, as well as practical, to obtain high quality schlieren photographs at densities less than 1% of atmospheric. Although the use of sodium vapor as a contaminent for enhancing the refractivity is limited to gases that do not react with sodium and to temperatures below that at which sodium ionizes, there is clearly a great deal of room for elaboration and improvement of the technique.

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Resonance Scattering Technique for Low Density Experiments

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Known density changes as small as 10^{-7} atm have been observed photographically by use of Na resonance radiation.

THERE is an urgent need for new optical techniques to observe small densities or density variations (e.g., shock waves and boundary layers) under conditions of extremely small ambient densities. The conventional schlieren system used in aerodynamic research reaches its limit of sensitivity at ambient densities of approximately 10^{-3} atm. For this reason, work is in progress at this laboratory to develop optical techniques for flow visualization at densities several orders of magnitude lower.

The purpose of this note is to describe a technique for obtaining observable changes of density as low as 10^{-4} mm Hg under steady-state conditions. This allows the development of optical instrumentation for observing small density changes without the difficulties of the short flow durations present in shock tubes and similar facilities.

Resonance Scattering

To observe the behavior of a low density gas, the emitted radiation may be analyzed. The excitation of the atoms is produced by high temperature, by an incident electron beam, or by microwaves, etc. It appears, however, that resonance scattering has not been used extensively in low density aerodynamic research. This method is based on the fact that the absorption and scattering cross sections of resonance photons, incident on a gas, are very large (1).[3] Therefore, if one observes, e.g., low density sodium gas in a beam of sodium light, the effects of scattering, absorption, etc., are greatly increased compared to nonresonance light.

In the case where the line width of the incident light is broad compared to the line width emitted by the gas, the resonance scattering behaves as if two independent processes, an absorption and subsequent emission, took place. The resonance absorption cross sections can be calculated for the center of a spectral line as

$$\sigma = \tau^2/2\pi \qquad [1]$$

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[3] Numbers in parentheses indicate References at end of paper.

For the present case, with $\lambda = 6000$ A, $\sigma = 6 \times 10^{-10}$ cm^2 is obtained. Therefore, number densities of the order of 10^{10} cm^{-3} should be observable provided the intensity of incident light is sufficient.

Experiment

The experimental apparatus is shown in Fig. 1. Sodium is heated in the platinum boat *R* by an a.c. current. The platinum boat is constructed from a 2-mil platinum strip, approximately 6 cm long. A bell jar *B* is placed over the boat and is sealed to the base plate by an *O*-ring. The system is evacuated by a diffusion pump, which is backed by a mechanical boost pump. An iron constantan thermocouple is placed in the bottom of the boat and passes through the base plate *G* to the recording pyrometer. The source of

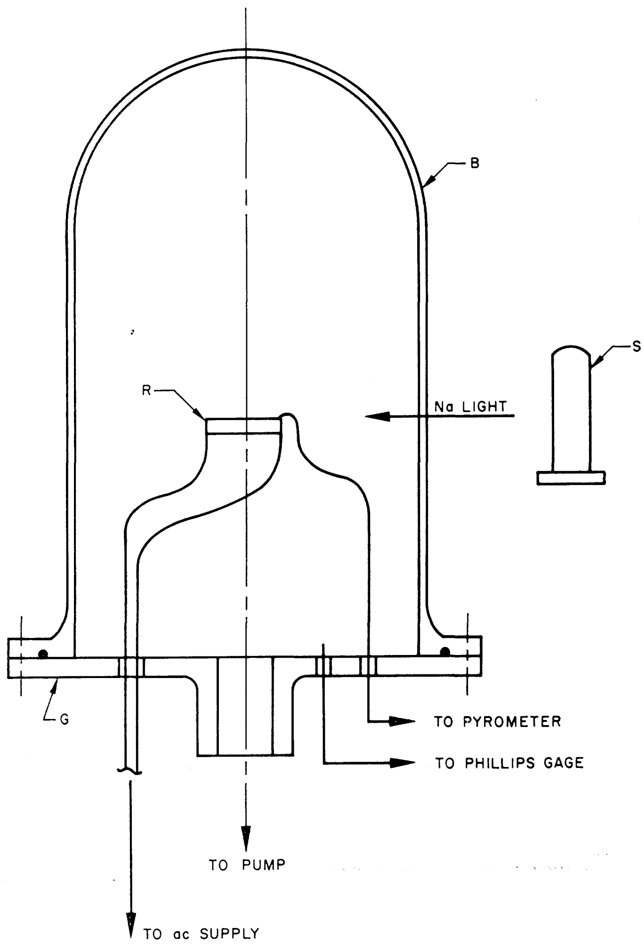

Fig. 1 Diagram of the apparatus

sodium light is an Osram lamp *S*. To eliminate reflections from the bell jar, an aluminum foil was placed over the source side of the bell jar with a 2-in. diam hole for admitting the sodium light. The radiation scattered from the Na vapor is observed at right angles to the incident light with a conventional Polaroid camera using Polaroid 3000 ASA film. The pressure in the bell jar is monitored by a Phillips vacuum gage.

In operation, solid Na is placed in the platinum boat, and the thermocouple is embedded in the Na. The system is evacuated to the desired ambient pressure. The boat is heated until radiation is observed by eye in the vicinity of the boat. The observed radiation takes an approximately spherical shape around the boat. The size of the sphere may