An Extended Use of the Hydrogen Bubble Flow Visualization Method

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THE establishment of the hydrogen bubble flow visualization method as an experimental tool for both quantitative and qualitative measurements for study of flows in a water medium has now been well made. The success of this instrument over less or better known techniques can be summarized briefly by the following points: 1) it does not permanently discolor the fluid; 2) the small size of generating wire minimizes the possible disturbance to the flow proper; 3) the use of combined streak lines gives a comprehensive picture of the velocity field of unsteady flows;[1] and 4) tracer particles are easily placed in the flow at any desired location.

Sources of error have been extensively analyzed,[1] and the accuracy has been demonstrated to be at least as good as any other method available for use in water. Even more recent work at the David Taylor Model Basin has shown that it is now possible to use the bubble with a flow velocity as high as 20 ft/sec.[2] The low velocity had previously been a limitation. The purpose of this note is to report yet another extension and possibility for investigation: namely, measurements in liquid-water mixtures. Specifically, excellent success of the hydrogen bubbly method was achieved in a glycerine-water mixture up to 40% (by weight) of glycerine.

Constant time lines were generated by energizing a wire with a Hewlett-Packard 214A pulse generator, which had to be operated at maximum amplitude, when a pulse width of 5.0 msec was required to produce lines that could be photographed. At speeds up to 1 fps, such a pulse width gave clearly defined lines, but at higher speeds the lines became progressively more ragged, which would badly reduce the accuracy of quantitative data. Excellent streak lines were produced by a 3-in. length of kinked wire by an applied d.c. source of 30–50 v.

Glycerine-water mixtures became permanently cloudy with continued use; lighting therefore requires careful attention.

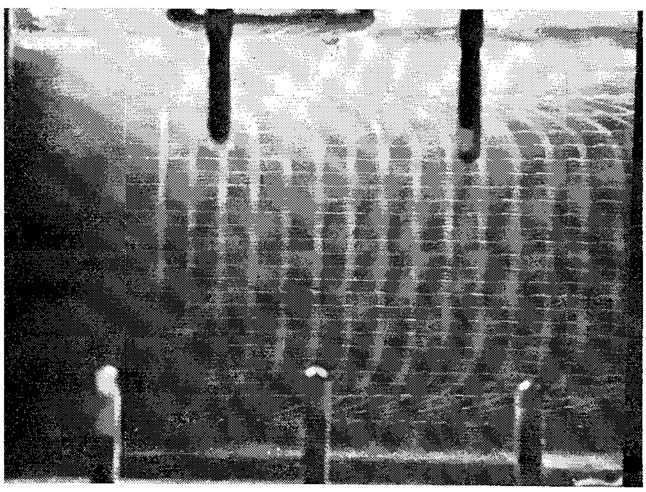

Fig. 1 Developing plane Poiseuille flow in glycerin-water mixture (35% by weight).

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A sharply collimated source proved most effective, whereas the use of matt-black paint whenever possible helped to reduce light scatter. More efficient filtering of the water supply or purer water might eliminate this difficulty.

A typical photograph taken in a 35% mixture is offered as a sample of the mixture usage (Fig. 1). This picture was made in a channel 3 in. deep, 12 in. wide, and 6 ft long, as a plane Poiseuille flow was developing from rest. The pulsing wire used was one of the kinked variety, and for reference the pulse lines (actually bands) are $\frac{1}{20}$ sec apart.

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Transient Stresses in Solids Induced by Radiant Surface Heating

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IF the surface of a solid is exposed to a very high rate of radiant heating, transient stresses may be induced either by thermoelastic coupling at low surface temperatures or by rapid vaporization at high surface temperatures. The magnitude of both of these phenomena is strongly dependent upon the rate at which energy is supplied to or absorbed at the surface. This note will discuss some preliminary considerations and describe experiments on rod-type specimens heated in an arc-imaging facility.

If the free surface of a solid is suddenly heated, it is possible to generate elastic stress waves propagating from the surface into the solid. This problem was first specifically analyzed by Danilovskaya[1] in 1950, although the governing equations have been available for some time. Since 1950, a large number of theoretical papers have appeared,[2] and within the last few years qualitative experimental evidence has been obtained.[3–5] The stresses considered are developed solely from the inertial restraint of the thermally expanding material, so that it is necessary to heat the surface extremely fast in order that appreciable particle accelerations are induced. In fact, the rise time of the surface temperatures must be short compared with the characteristic mechanical response time of the solid.

The experimental evidence for this phenomenon has been obtained with pulsed (on the order of 1 μsec or less) energy sources. These include exploding wires,[3] pulsed lasers,[4, 5] and pulsed microwave energy and electron beams.[4] The results all show pressure signals detected at positions remote from the radiated surface and arriving at times appropriate for propagating elastic waves. Quantitative agreement is not always possible because of the difficulty in prescribing the amplitude and distribution of the absorbed energy.

If the total energy input as well as the flux or power density is large, the surface rapidly reaches the vaporization temperature, and a pressure is established proportional to the rate of

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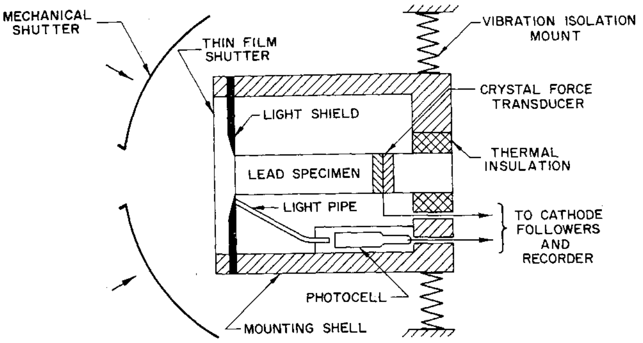

Fig. 1 Schematic of specimen for transient pressure measurements.

mass loss $\dot{m}$. This pressure P results from the momentum change at the surface such that[6]

$$P = \dot{m}v \tag{1}$$

where v is the mean efflux velocity of the vapor. The steady-state mass-loss rate is given approximately by

$$\dot{m} \approx \alpha H/L \tag{2}$$

where H is the incident power density, α is the proportion of the incident flux used in vaporization, and L is the heat of vaporization. The pressure is thus directly proportional to the magnitude of the incident flux.

A simple experiment was set up in order to detect transient stresses in a rod-type specimen resulting from a high thermal flux at one end. Lead was chosen for the specimen material because of its relatively high coefficient of expansion, low elastic wave velocity, and low vaporization temperature. The radiant energy source was an arc-imaging furnace capable of supplying a continuous flux of up to 1000 cal/cm^2-sec. The radiation from the arc was focused on the face of the specimen by means of two parabolic mirrors, the specimen being located in a pressure/vacuum-tight chamber. The focal spot diameter is approximately 1.5 cm.

A schematic of the specimen is shown in Fig. 1. The force transducer is a lead mitoniobate crystal in series with the cantilevered, rod-type specimen. The distance between the crystal and the exposed surface was sufficient that the temperature at the crystal did not rise during the period of exposure. The crystal was also shielded against direct radiant heating. A light pipe and photocell were situated to record the rise and decay of the incident flux. The shell supporting the specimen was mounted so as to isolate the specimen from vibrations occurring in the arc chamber. Outputs from the crystal and photocell were recorded on either an oscilloscope or oscillograph.

In order to obtain a sharp rise time on the thermal flux, it was necessary to develop a fast-acting shutter, since the rise time on the flux emanating directly from the arc when it is struck is comparatively long because of inductance in the circuit. A solenoid-operated, mechanical, clam-shell shutter having an opening time of 40 msec is part of the specimen chamber. A faster shutter is necessary to generate the temperature-time histories required to initiate an elastic wave. Optical shutters of the Kerr cell type are not applicable because of the high flux levels involved. The optimum shutter devised consisted of a thin, $\frac{1}{4}$-mil, mylar film stretched over the face of the mounting shell. The front surface of the film was vacuum deposited with aluminum. Because of its initial high reflectivity, the film absorbed heat slowly and then vaporized rapidly. An effective opening time for this shutter was found to be 1 to 1.5 msec on the basis of fastax pictures taken during an actual run.

The pressure signals recorded from the specimen could be correlated only with transient vaporization and not with any thermal initiation of stress waves. The absence of pressure signals arriving at the elastic wave transit time can be attributed to an insufficiently sharp rise time on the incident flux. Pulsed energy sources will be more applicable in the study of this type of phenomenon.

Figure 2 shows a record of the pressure signal from the lead rod at an incident flux level of approximately 600 cal/cm^2-sec and an ambient pressure of 50 μ Hg. The upper trace indicates the opening and closing time of the mechanical, clam-shell shutter. The middle trace is the output from the photocell, from which it can be noted that the thin film shutter is vaporized before the mechanical shutter is completely open. The pressure signal (on the lower trace) corresponds closely to the duration of exposure of the specimen. The short delay on the rise time is dependent on the temperature rise at the surface. The decay of the pressure signal coincides with the closing of the mechanical shutter, after which the surface cools rapidly. Because of charge leakage from the piezoelectric crystal, the pressure signal drops somewhat below its initial value.

After the initial rise, the pressure signal reaches a nearly constant value, probably corresponding to a constant surface temperature. The maximum pressure in the record of Fig. 2 is 2.0×10^4 dynes/cm^2. In order to calculate the pressure from Eqs. (1) and (2), we would first have to assume a value for α. Rather than do this, we will calculate α from the measured values of P and H, the known value of L (223 cal/gm), and an efflux velocity of the vapor based on the assumption that the vapor is in equilibrium with the surface temperature T_s, taken as the equilibrium boiling temperature of lead at 50 μ Hg ambient pressure ($T_s = 1100°$K). Thus, v is assumed given by

$$v = (3RT_s/M)^{1/2} \tag{3}$$

In this manner, $\alpha = PL/Hv$ is found to be 0.20. This is a very reasonable value when the finite emissivity of the surface and conductivity in the solid are considered, as well as the other approximations made. The problem is further complicated by the fact that a melt phase was also formed, and there existed, in fact, two phase boundaries propagating into the solid simultaneously. Masters[7] has obtained numerical solutions for the internal temperature distribution for this problem under certain simplifying assumptions.

The transient pressures measured appear to be in qualitative agreement with predictions based on rapid vaporization from the surface. More quantitative agreement will require accurate knowledge of the surface emissivity, surface temperature, and internal energy distribution in the solid or melt. For multiphase materials or reacting atmospheres, prediction of transient pressures will be further complicated by additional surface and internal, rate-controlled chemical reactions.

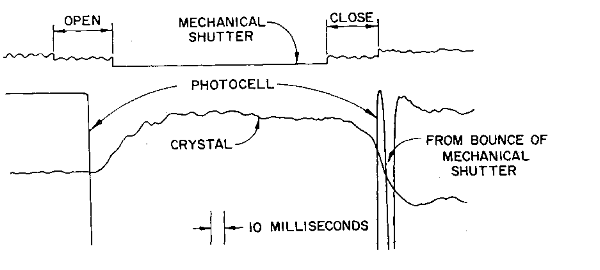

Fig. 2 Shutter, photocell, and force transducer signals during vaporization experiment.

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Shock-Layer Radiation for Yawed Cones with Radiative Decay

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APPROXIMATE methods for determination of the effect of radiative decay on the shock-layer radiation toward sphere-cones under zero angle of attack have recently been presented by Chin and Hearne.[1] In this note, these methods are extended for application along the windward line region of circular cones at finite angle of attack.

Figure 1 shows the geometry of a circular cone of half-angle θ_c at an angle of attack α with the freestream. The shock layer is assumed to be very thin compared with the local radius so that the half-angle of the conical shock wave θ_s is approximately that of the body, or $\theta_s \approx \theta_c \approx \theta$. In the immediate region along the windward line, the three velocity components at the entry point (S_i, ϕ_i) immediately behind the shock wave can be shown to be

$$u_c/u_\infty \approx \cos(\theta + \alpha) \tag{1}$$

$$u_\phi/u_\infty \approx \phi \sin\alpha \tag{2}$$

$$u_s/u_\infty \approx \epsilon \sin(\theta + \alpha) \tag{3}$$

where u_c, u_ϕ, and u_s are the velocity components along a conical ray, in the ϕ direction, and normal to the shock wave, respectively; and ϵ is the density ratio across the oblique shock wave.

The exact path of a fluid particle subsequent to its entry within the radiating shock layer cannot be simply determined. However, the entry point (S_i, ϕ_i) for the streamline passing the point (S, ϕ, y_a) may be approximated in several alternative ways. Considered first is the case in which the peripheral acceleration due to the ϕ pressure gradient is neglected. The streamlines follow a geodesic path. The magnitude and direction of the velocity remain unchanged in the developed surface. For this case, the time required for a particle to travel from (S_i, ϕ_i) to (S, ϕ, y_a) may be written as

$$t = (S - S_i)/u_c = [S \sin\theta(\phi - \phi_i)]/[u_\phi(\phi_i)] \tag{4}$$

where $u_\phi(\phi_i)$ is a function of ϕ_i, and

$$y_a = \int_0 \frac{\rho}{\rho_s}\, dy$$

is the Howarth-Dorodnitsyn variable.

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From a continuity consideration,

$$u_s S_i \sin\theta dS_i d\phi_i = u_c S \sin\theta dy_a d\phi \tag{5}$$

By manipulation of Eqs. (1–5), the following equation may be derived:

$$d(y_a/S) = \epsilon \tan(\theta + \alpha)\zeta d\zeta/(1 + C - C\zeta) \tag{6}$$

where

$$\zeta = S_i/S \qquad C = \sin\alpha/[\cos(\theta + \alpha)\sin\theta]$$

The parameter C may be termed a "crossflow" parameter. Integration of Eq. (6) yields the following expression:

$$\frac{y_a}{S} = \frac{2}{C}\left\{\frac{1}{C}(1 + C)\ \ln\left(\frac{1 + C}{1 + C - C\zeta}\right) - \zeta\right\}\frac{\epsilon}{2}\ \tan(\theta + \alpha) \tag{7}$$

By letting $\zeta = 1$, Eq. (7) yields

$$\frac{\Delta a}{S} = F\,\frac{\epsilon}{2}\tan(\theta + \alpha) \tag{8}$$

where Δ_a is the adiabatic shock-layer thickness, and

$$F \equiv \frac{\Delta_a/S}{(\epsilon/2)\tan(\theta + \alpha)} = 2\,\frac{(1 + C)\ln(1 + C) - C}{C^2} \tag{9}$$

When $\alpha = 0$, $F = 1$, and Eq. (8) becomes identical with the constant-density solution for a circular cone at zero angle of attack.[2] The factor F therefore represents the effect of crossflow on Δ_a/S at the windward line relative to the case with an equivalent cone half-angle $(\theta + \alpha)$ and without crossflow; hence, F may be termed the crossflow factor.

Equations (7) and (8) may be combined to yield

$$\eta \equiv \frac{y_a}{\Delta_a} = \frac{(1 + C)\ln\left(\frac{1 + C}{1 + C - C\zeta}\right) - C\zeta}{(1 + C)\ln(1 + C) - C} \tag{10}$$

The energy balance along the streamline may be written as follows:

$$-u(dh/ds) = u_c(dh/dS_i) = 4\sigma k T^4 \tag{11}$$

where u is the velocity along the streamline direction s, h the enthalpy, k the Planck-mean mass absorption coefficient, σ the Stefan-Boltzmann constant, and T the absolute temperature.

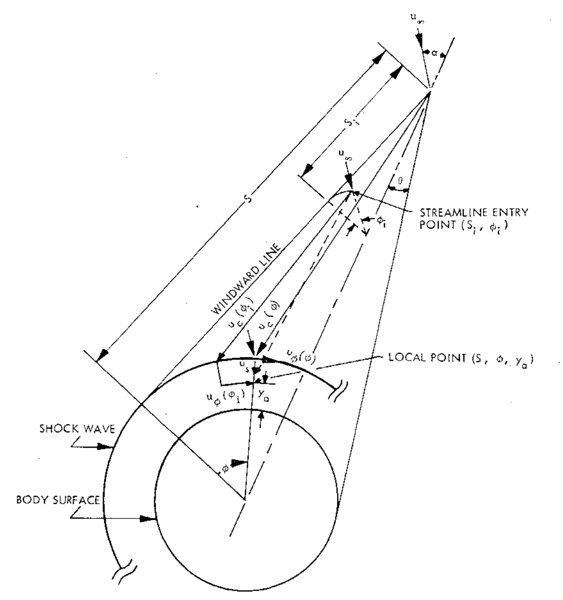

Fig. 1 Geometry of circular cone at angle of attack.