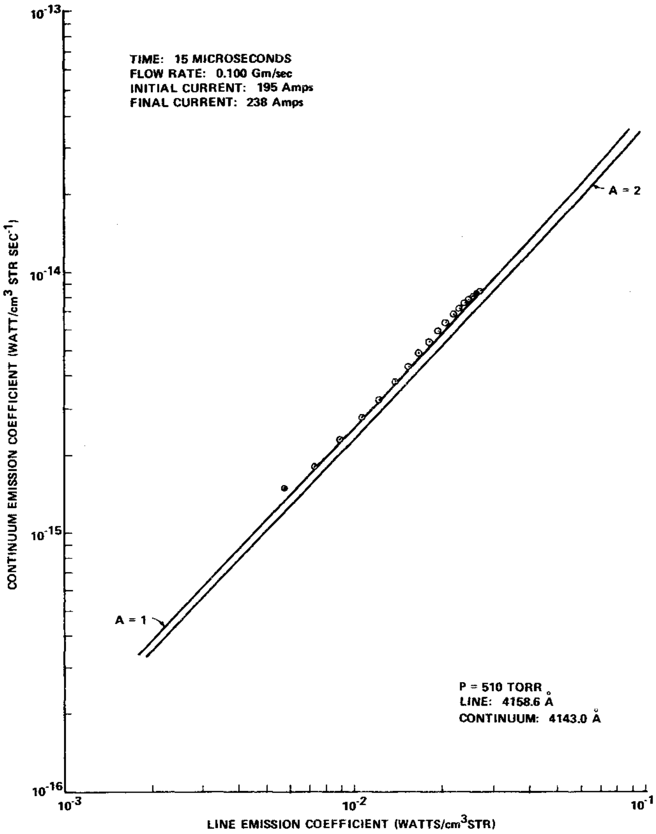

Fig. 3 Emission coefficients, 15μsec into transient.

of the pulse. Information on equilibrium was obtained through comparison of experimental and theoretical emission coefficients.[1,2] [In the computations,[2] $A = 1, 2$ (where A is the ratio of the electron temperature to the heavy particle temperature) were employed.] The gaunt factor in the equation for continuum radiation was determined in the initial steady state from a best fit with the corresponding line radiation. The values of the gaunt factor so obtained were 1.63 at 820 and 1120 torr, and 1.80 at 510 torr. In Ref. 3, at the wavelength of interest, at arc temperatures about 12,000 K, and for pressure levels of 760 and 1520 torr, a value of 1.80 was obtained. In Ref. 4, at atmospheric pressure, at a temperature of 12,000 K, the gaunt factor was found to be about 1.4 at the wavelength of interest.

In Figs. 2 and 3 are shown curves of the experimental and theoretical continuum and line emission coefficients for the initial steady state and 15 μsec into the transient, respectively; pressure level is 510 torr. Such results have indicated the arc to be in local thermal equilibrium down to at least the $3P_6$ level. The result is probably strongly influenced by the relatively long rise time of the applied voltage pulse. Continuous monitoring of the dynamic behavior of the radiation at a given chordwise station has shown a monotonic increase in intensity with time following initiation of the transient. Experiments on rapidly (in the $n$sec–μsec range) crowbarred atmospheric argon arcs[5-7] have indicated an initial increase in arc radiation for times of the order of 100 $n$sec; these increases appear to be related to nonequilibrium distributions in the bound and free energy levels.

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Variable Energy Blast Wave Measurements

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Introduction

THE instantaneous input of a large quantity of energy in an infinitesimally small volume of a gaseous medium produces a strong shock wave front with a flowfield as described by the classical blast wave analysis. Such blast waves have been analyzed by several authors.[1-4] More recently, treatment of the classical blast wave has been extended[5,6] from the classical instantaneous energy addition to the case of injection of energy as a given function of time. Some of the latter work[5] was done in connection with interest in spark discharges in which energy transfer at a rate proportional to time was considered. More generally, in connection with detonations, a variable rate of energy input proportional to time to a constant exponent (t^β) was considered.[6] In the more general treatment, $\beta = 0$ would represent the classical case of instantaneous energy input, $\beta = 1$, the energy input proportional to time, and β equal to other values to possibly be employed to simulate certain detonation conditions. The purpose of this Note is to report on measurements of parameters for the case of variable energy input blast waves and to show a comparison of the measurements with the predictions of the available theory.

Apparatus

A low inductance exploding wire circuit was employed so that the energy stored in a large capacitor (14.7 μfd/20 KV Sangamo) could be discharged in an "optimum" fashion[7] with energy transferred to the wire in a single pulse with no oscillation of current and voltage and no dwell time and restrike. A noninductive current shunt (T and M Co.) was used to measure current as a function of time, and the voltage across the wire was measured with a P-6015 Tektronix High Voltage Probe.

Schlieren photographs were taken with an ultra-high speed framing camera (Beckman-Whitley no. 330) capable of up to 2×10^6 frames/sec. The field of view was $\sim 2\frac{1}{2}$ in. in diameter. The wire was exploded at ambient conditions. Number 26 gauge silver wire extending $1\frac{1}{2}$ in. in length between terminals was

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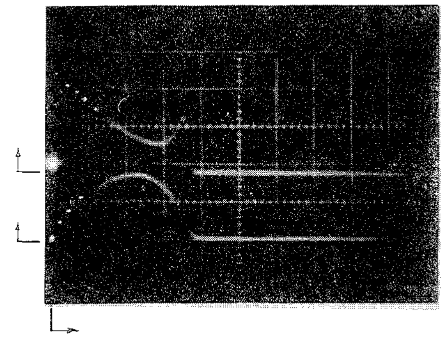

Fig. 1 Voltage and current traces. Upper trace 2 KV/div; lower trace 20 KA/div; sweep speed 1 μsec/div.

employed. Plexiglas plates were used to confine the expansion at the wire ends for true cylindrical symmetry. An ultra high-speed oscilloscope was used to check the initial voltage rise.

Results and Discussion

Current and voltage wave forms are shown in Fig. 1. Only conditions for a single pulse discharge (infinite dwell or no restrike) were employed. Energy input as a function of time was determined by multiplying current times voltage and integrating over short time intervals. Figure 2 shows such an energy-time graph. Unfortunately this method of graphically determining energy is only accurate to $\sim 10\%$.

Schlieren photographs of the flowfield generated by the exploding wire are shown in Fig. 3. The speed at which the pictures were taken was $\sim 10^6$ frames/sec. Figure 3 shows frames 2.02 μsec apart with the first frame shown taken at 0.8 μsec after initiation of the energy transfer. (The thick line shown as $1\frac{1}{2}''$ long in the bottom of frame (1) is the wire.) The shock can be seen to move ahead away from the cloud of metal vapor at ~ 15 μsec or ~ 1.9 cm from the center (original position of the wire). The high density of silver vapor prevents passage of light through the vapor cloud at the center and out to the contact surface. After the shock moves out the contact surface appears to become unstable and irregular. (The wire is seen in later exposures as a result of double exposure.) The shock front location as a function of time is shown in Fig. 4.

The photographs in Fig. 3 were taken with an offset creating some relief at one end of the wire and the shock can be seen curving around at that end of the wire. It is interesting to note that the vapor cloud moves radially outward even at the end with the relief and does not extend into the relief region as the shock does. The pictures taken under the same conditions except with both end plates flush at the wire end with no relief, yield essentially the same curves as shown in Fig. 4. In Fig. 4 the circles correspond to the photographs shown in Fig. 3, while the squares and triangles are from pictures with side plates flush with the end of the wire.

If the energy input shown in Fig. 2 is approximated by an exponential of time, the analysis for variable energy blast waves[6] yields the theoretical curves shown in Fig. 4. Results are shown

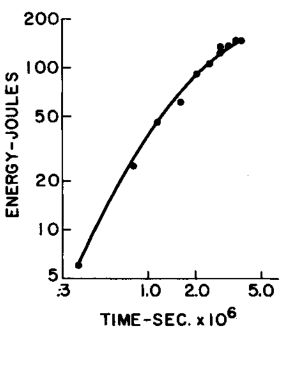

Fig. 2 Energy transferred as a function of time.

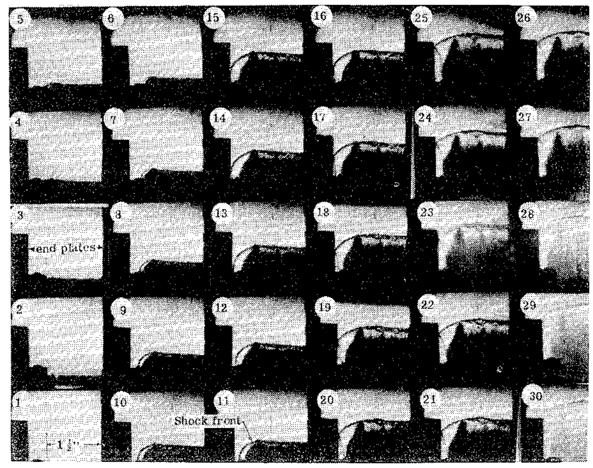

Fig. 3 Schlieren photographs of exploding wire. Frames are 2.02 μsec apart.

for $\beta = 2$, $\beta = 1$ and $\beta = 0$ (instantaneous energy transfer) for energy input assumed proportional to t^β where the modified blast wave theory[6] for cylindrical symmetry yields

$$R = \left[\frac{a_o^2 E}{p_o^2 \pi l}\frac{1}{J_o t_i^\beta}\left(\frac{4}{\beta+2}\right)^2\right]^{1/4} t^{(\beta+2)/4} \tag{1}$$

where, in the nomenclature of Ref. 6, R is the shock radius; a_o is the speed of sound in the ambient gas; p_o is the pressure of the ambient gas; E is the total energy transferred; l is the length of wire; t_i is the time it takes to transfer the energy; J_o is a constant calculated by numerical integration of energy equation and taken from results in Refs. 4 and 6; β is the exponent from the energy transfer curve and t is time. For the case shown in Fig. 4, t_i was 3.8×10^{-6} sec, and E was 146 joules. J_o was taken as 0.878 for $\beta = 0$, 0.56 for $\beta = 1$, and 0.51 for $\beta = 2$. $\beta = 2$ approximated the energy curve (Fig. 2).

Conclusions

Measurements of energy transfer to a gaseous medium as a function of time combined with measurements of location of shock front as a function of time provides a good test for existing blast wave theories. The measurements employing exploding wires show that the classical blast wave theory, for instantaneous energy release, applies reasonably well "long" after the com-

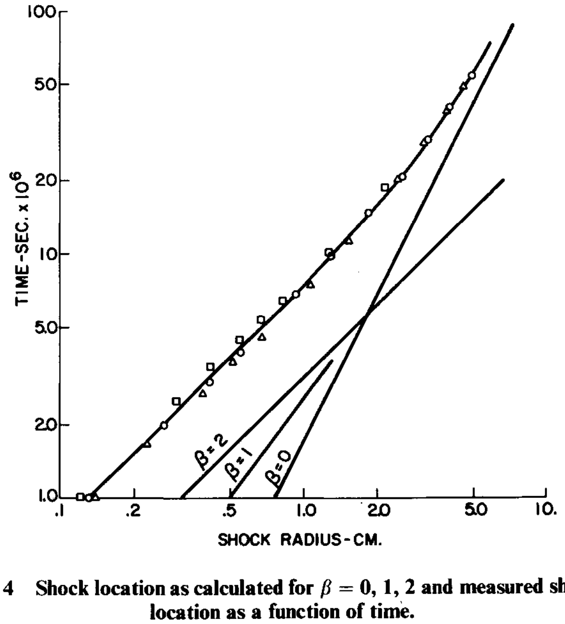

Fig. 4 Shock location as calculated for $\beta = 0, 1, 2$ and measured shock location as a function of time.

pletion of the energy transfer. However, although the "functional relationship" between shock location and time is remarkably close to the prediction of the theory as modified for "variable energy" blast waves, Eq. (1), a modified constant is required for a good match. In the present case with $\beta = 2$, ratios of shock arrival times at two fixed locations are predicted remarkably well by the expression

$$t_2/t_1 = (R_2/R_1)^{4/\beta+2} \tag{2}$$

given by the modified blast wave theory.

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Incipient Separation of Axially Symmetric Hypersonic Turbulent Boundary Layers

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Introduction

In a recent Note, Rose Page and Childs[1] showed that the pressure rise for incipient separation in axially symmetric internal supersonic flow could be considerably lower than for planar, two-dimensional flows. However, for axially symmetric external supersonic flow Kuehn[2] found that the turbulent boundary layer can withstand a slightly larger pressure gradient before separation occurs. The present hypersonic cold wall experiments have confirmed Kuehn's result and have emphasized the close relation between the axisymmetric and two-dimensional cases. This similarity suggests that criteria evolved from the large amount of available two-dimensional data may be used in the design of control surfaces for hypersonic vehicles.

Experimental Details

The experiments were conducted at a freestream Mach number of 9 in the Imperial College No. 2 Hypersonic Gun Tunnel,[3] using Nitrogen as the test gas. The model was a sharp leading edge hollow cylinder of 6.4 cm outside diameter to which could be added trailing edge flares with angles in the range $15° < \alpha < 40°$. Both the cylinder and the flares were instrumented with surface pressure tappings and thin film gauges for heat-transfer measurement. The length of the cylinder ahead of the flare was 45.7 cm.

All tests were conducted with the cylinder axis parallel to the freestream. The experimental data have been tabulated by Coleman.[4]

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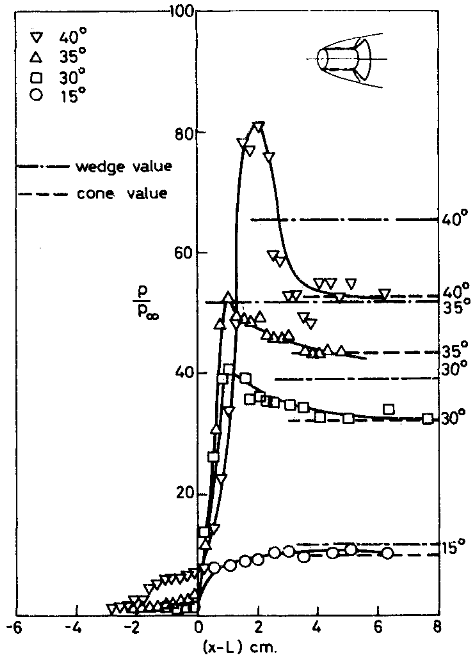

Fig. 1 Pressure distributions on a hollow cylinder-flare; $M_\infty = 9.22$, $Tw/Tr = 0.28$, $Re_{\delta_L} = 2.14 \times 10^5$.

Discussion

The surface pressure distributions (Fig. 1) were similar to the two-dimensional data (Fig. 2) reported by Elfstrom.[5] Elfstrom noted that, for two-dimensional hypersonic flow, the incipient

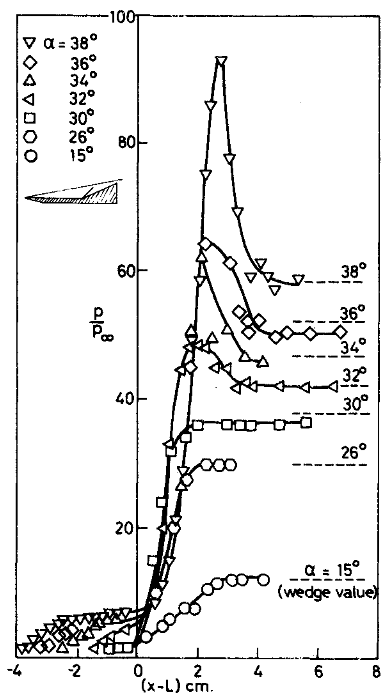

Fig. 2 Pressure distributions on a wedge compression corner (Elfstrom[5]); $M_\infty = 9.22$, $Tw/Tr = 0.28$, $Re_{\delta_L} = 3.4 \times 10^5$.