Acoustic Thermometric Measurements of Propellant Gas Temperatures in Guns

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A technique is developed that permits propellant gas temperature to be extracted from pressure measurements taken within the gun tube. Basically similar to acoustic thermometry, the wave speed of a signal propagating at the sonic velocity is determined. In this application, the speed of the expansion wave that propagates back up the gun tube following shot ejection is derived from pressure data taken at discrete axial locations within four calibers of the muzzle of a 20-mm gun. The propellant gas temperature is calculated from the measured speed of this wave and the equation of state.

Introduction

THE muzzle blast generated during weapon firing (Fig. 1) is driven by the expanding propellant gases ejected subsequent to projectile launch. It is of interest to model the blast field to determine its environmental signature and its effect upon the projectile trajectory. Any quantitative model of this flowfield requires the specification of accurate initial conditions, i.e., propellant gas properties at the muzzle during gun tube emptying. The propellant gas properties predicted by interior ballistic models[1-3] are dependent upon the method of treating the combustion and gasdynamic processes occurring within the gun tube. In general, the validity of these models is gauged against the accuracy with which they predict projectile acceleration and in-bore pressure histories. These parameters are not sufficient for muzzle blast calculations.

A propellant gas property of particular importance is temperature. The development of the muzzle blast has been shown[4,5] to obey the predictions of spherical, strong blast theory[6] based upon the initial rate of energy efflux from the muzzle. Gas temperature has a significant influence upon the initial rate of energy efflux. This may be demonstrated by considering the one-dimensional flow of an ideal gas. The energy flux past any station at a given time is

$$\dot{E}=\rho u\left(c_v T+\frac{u^2}{2}\right)A=\frac{pu}{\gamma-1}\left[1+\frac{\gamma(\gamma-1)}{2}\left(\frac{u}{a}\right)^2\right]A \quad (1)$$

Neglecting the projectile presence and two-dimensional effects, the idealized flow geometry shown in Fig. 2 is used to approximate the arrival of the propellant gases at the muzzle and subsequent expansion of these gases once the muzzle is breached. Using one-dimensional, unsteady flow theory,[7] an expression for the ratio of incident rate of energy flux, $\dot{E}_I$ to rate of energy passing the muzzle $\dot{E}^*$ may be derived that is only a function of the ratio of specific heats and incident Mach number u_I/a_I. For $\gamma=1.25$, this ratio is plotted vs u_I/a_I in Fig. 3. The energy flux ratio $\dot{E}^*/\dot{E}_I$ varies strongly with incident Mach number in the range $0<u_I/a_I\leq 0.6$. As the sonic condition is approached, the energy flux ratio asymptotes toward unity due to decreasing strength of the muzzle expansion. For sonic and supersonic values of u_I/a_I, there is obviously no return expansion from the muzzle. Since several important classes of weapons (e.g., mortars, howitzers) launch projectiles in the low incident Mach number regime, it is of interest to determine the detailed exit properties under these conditions.

A variety of techniques has been applied to the measurement of propellant gas temperature during the interior ballistic cycle. Thermocouples[8] have been mounted to the inner wall of the gun tube in attempting to directly measure gas temperature. Since flush-mounted devices are immersed in the propellant gas boundary/thermal layer, thermocouple output does not reflect temperature in the inviscid mainstream. Optical techniques such as two-color pyrometry[9] and spectroscopy[10,11] are also complicated by the presence of the wall boundary layer. Additionally, contamination of optical surfaces by particulate deposition during the measurement period further degrades these approaches. Klingenberg and Mach[11] present a calibration and data acquisition procedure that reduces the influence of this deposition on spectroscopic measurements; however, the effect of the wall thermal layer remains to be assessed.

In the present report, a novel method to obtain in-bore temperature measurements is presented. The approach is similar to that used in acoustic thermometry;[12] namely the velocity of propagation of an acoustic wave is determined by measuring the time required for it to travel a known distance.

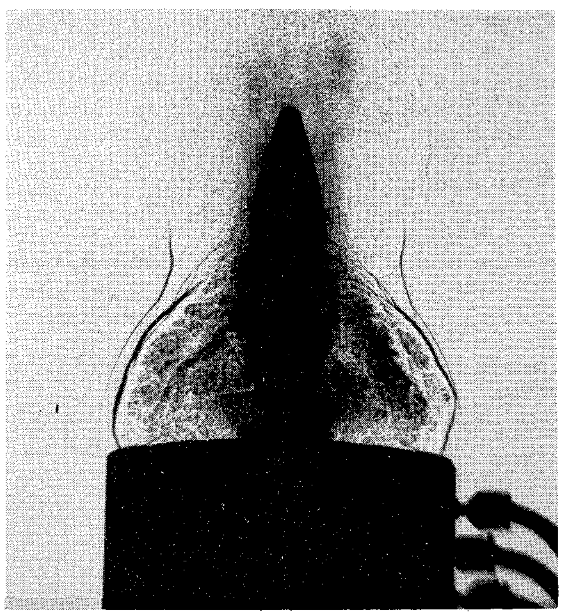

Fig. 1 Shadowgraph of muzzle blast.

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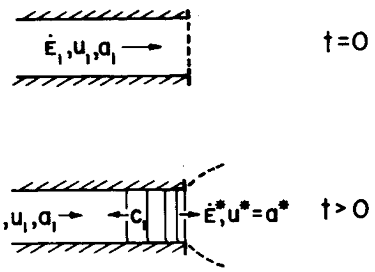

Fig. 2 Idealized, one-dimensional exit flow.

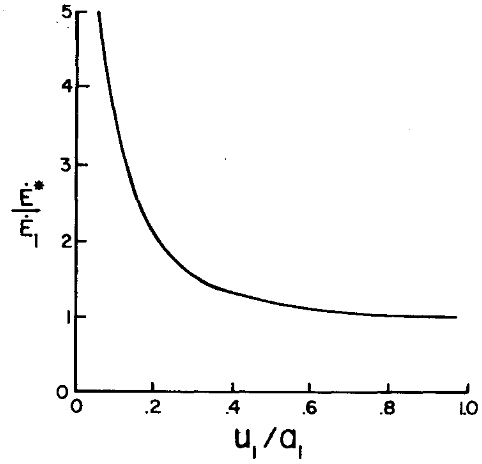

Fig. 3 Ratio of energy efflux rates vs incident flow mach number.

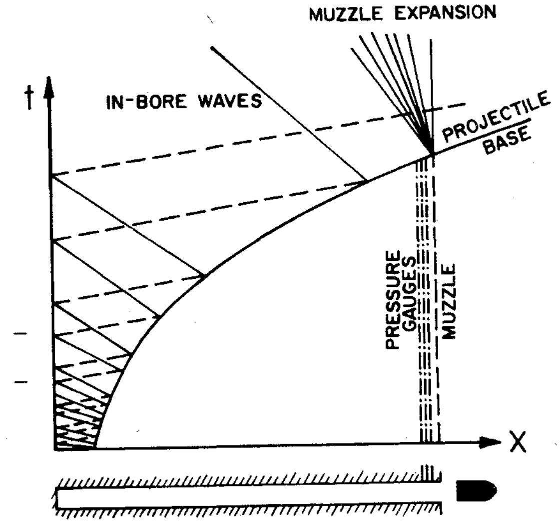

Fig. 4 In-bore wave diagram.

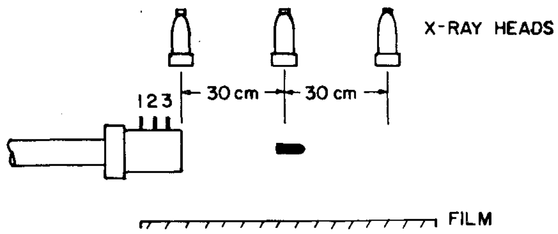

Fig. 5 Schematic of test setup.

Unlike acoustic thermometry in which an external signal is introduced into the test medium, the present technique measures the propagation velocity of an isentropic wave generated in the flow itself, the returning muzzle expansion (Fig. 4). Pressure transducers, flush mounted in the tube wall, are used to sense passage of the muzzle expansion. Since pressure signals are impressed across the wall boundary layer, its effects upon the measurements are minimized. The details of the instrumentation and data reduction procedures applied to a 20-mm gun will be presented in the subsequent sections.

Instrumentation and Experimental Data

A schematic of the test setup is shown in Fig. 5. Data are taken on the launch of a standard, 98 g, training projectile from a 20-mm gun. The gun has a length of 152 cm, chamber volume of 41.7 cm^3, and twise of rifling of one turn in 25 calibers. Launch velocities ranging from 200 through 1000 m/sec were obtained by varying the mass of WC 870 propellant from 3.6 through 38.9 g, respectively. Launch velocity was measured from flash X-rays taken at three stations covering the first 60 cm of projectile flight.

A muzzle adaptor, having an overall length of 8.6 cm (Fig. 6), was fabricated to accommodate and shock mount the array of pressure transducers. Three Kistler, 603 A, piezoelectric pressure transducers are spaced at 2.5 cm intervals from the front face of the device. The output of the transducers is recorded on Tektronix, Type 551, Dual-Beam Oscilloscopes. A uniform time base between traces is provided by triggering all scopes simultaneously from the output of gage 1 as the projectile passes. Additionally, the discharge of the first X-ray tube is placed on each oscilloscope record by chopping the lower beam. In this manner, the projectile location may be related to the measured pressure variations.

A sample set of pressure traces obtained for a launch velocity of 366 m/sec is shown in Fig. 7. As the projectile passes gage 1, all scopes are triggered simultaneously. When the projectile passes a gage location, there is a rapid pressure rise as the gage becomes exposed to the high pressure

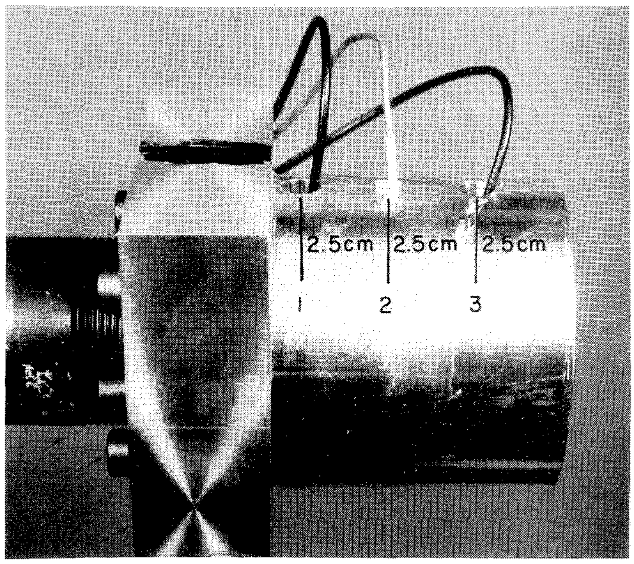

Fig. 6 Muzzle adaptor.

propellant gases. Naturally, gage station 1 is exposed first, followed by stations 2 and 3. As the projectile moves down the tube, in-bore waves reflected from the breech and the projectile base pass the gage location. This results in a gradual decay of the measured pressure at the gage station.

When the projectile clears the muzzle, the propellant gases expand into the surrounding atmosphere. Simultaneously, an expansion propagates into the gun tube bringing the muzzle to a choked or sonic condition. As the expansion passes the gage station, the pressure begins to decrease more rapidly. This is clearly observed as the sudden change in slope on the pressure traces. The wave is propagating into the gun tube; thus, it arrives at station 3 first and then moves to stations 2 and 1. The difference in arrival times is evident from the three traces

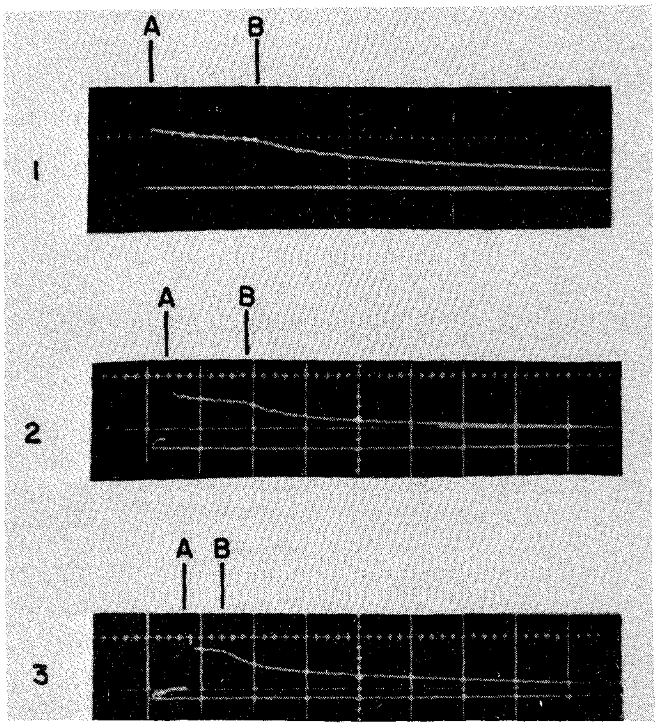

Fig. 7 Sample pressure traces at $u_m = 366$ m/sec. A: projectile passage. B: muzzle expansion passage.

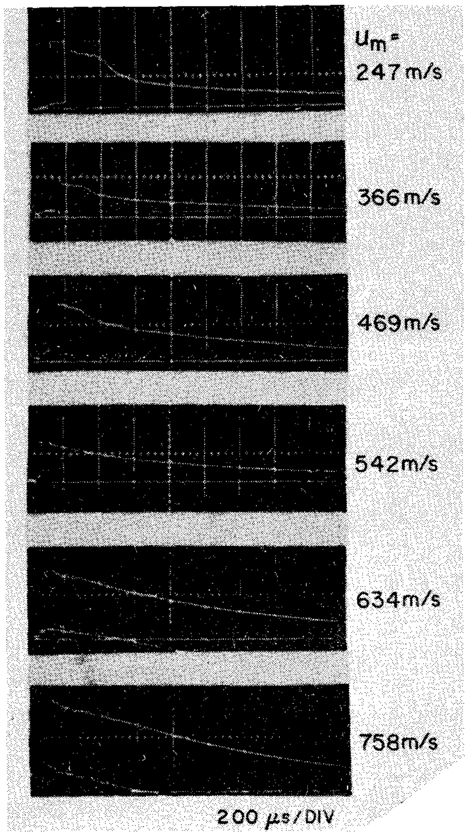

Fig. 8 Pressure traces from gage 3 at various launch velocities.

shown in Fig. 7. Since station 3 is closest to the center of the muzzle expansion, the rate of change of properties occurs very rapidly. As the muzzle expansion propagates further into the gun, it spreads out; thus the change in slope of the pressure traces is less severe. It is desirable to locate the pressure gages as near to the muzzle as possible in order to minimize property variation due to in-bore waves and to provide a strong signal upon passage of the muzzle expansion. This is particularly true at high launch velocities (Fig. 8). As the launch velocity increases, pressure decay due to in-bore waves arriving prior to the muzzle expansion becomes more severe. Simultaneously the strength of the muzzle expansion decreases. In the limiting case, the launch velocity increases to a point where the propellant gas reaches a sonic condition prior to shot ejection. When this occurs, there is no muzzle expansion into the gun tube.

Data Reduction and Presentation

A wave diagram of the near muzzle region is shown in Fig. 9. The goal of this technique is to determine the velocity of propagation of the lead wave of the muzzle expansion, m-f-d-b. The instantaneous velocity of a left running wave is

$$c = \frac{dx}{dt} = u - a \tag{2}$$

where u and a are the local flow velocity and speed of sound, respectively. The most direct means to obtain an estimate of the speed of sound is to assume the flow velocity is constant and equal to the launch velocity u_m, evaluate the wave speed using the measured arrival times at gage stations, and invert Eq. (2);

$$a = u_m - \frac{x_3 - x_1}{t_f - t_b} \tag{3}$$

This approach does not account for property variations occurring prior to arrival of the muzzle expansion as evidenced by pressure decay in Fig. 8.

A correction procedure may be developed from one-dimensional flow theory[7] if the flow is assumed to be locally

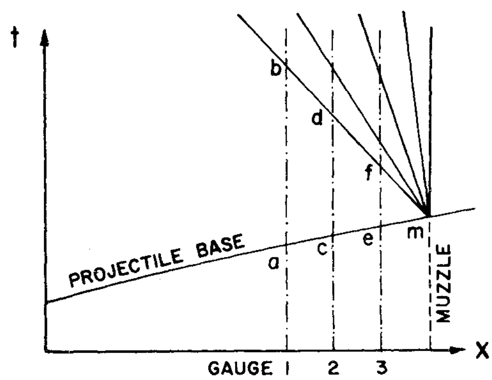

Fig. 9 Wave diagram of muzzle flow.

isentropic within test region, a-m-b. The following relation describes the property variations along a left-running characteristic or within a region of right-running simple waves

$$\frac{a}{a_1} = 1 + \frac{\gamma - 1}{2}\left(\frac{u}{a_1} - \frac{u_1}{a_1}\right) \tag{4}$$

where the subscript 1 refers to a suitable reference point. For isentropic flow

$$\frac{p}{p_1} = \left(\frac{a}{a_1}\right)^{2\gamma/(\gamma-1)} \tag{5}$$

These relations apply along the lead expansion wave m-f-d-b; however, there is no pressure gage exactly at the muzzle. This restricts the location of the initial reference point to be point e. The pressure-time history along the path e-f-d-b may be obtained from the measured data (pressures from e-f come directly from the trace of the third gage, pressures at d and b come from the intercept values on traces 2 and 1).

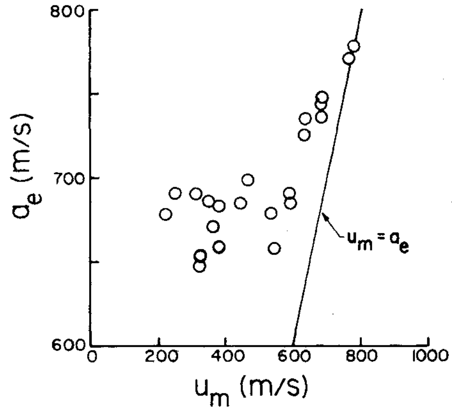

Fig. 10 Measured speed of sound.

If the projectile velocity is assumed to remain constant over the last 2.5 cm of travel through the device $u_e = u_m$, and if the path e-f is approximated as a simple wave region, Eq. (4) may be used to derive the following relation

$$\frac{u}{a_e} - \frac{a}{a_e} = \frac{u_m}{a_e} + \frac{3-\gamma}{\gamma-1}\frac{a}{a_e} - \frac{2}{\gamma-1} \tag{6}$$

Substituting Eq. (5)

$$\frac{u}{a_e} - \frac{a}{a_e} = \frac{u_m}{a_e} + \frac{3-\gamma}{\gamma-1}\left(\frac{p}{p_e}\right)^{(\gamma-1)/2\gamma} - \frac{2}{\gamma-1} \tag{7}$$

From Eq. (2), the incremental displacement dx of the lead wave in time dt is

$$dx = (u-a)dt = \left(u_m + \frac{3-\gamma}{\gamma-1}\left[\frac{P}{P_e}\right]^{(\gamma-1)/2\gamma} a_e - \frac{2a_e}{\gamma-1}\right)dt \tag{8}$$

This expression may be integrated over the path of the wave, f-d-b, and inverted to solve for a_e,

$$a_e = (\Delta x - u_m \Delta t) / \left(\frac{3-\gamma}{\gamma-1}\int_{t_f}^{t_b}\left[\frac{p}{p_e}\right]^{(\gamma-1)/2\gamma} dt - \frac{2}{\gamma-1}\Delta t\right) \tag{9}$$

where

$$\Delta x = x_b - x_f$$

$$\Delta t = t_b - t_f$$

All of the terms in Eq. (9) may be obtained from the pressure traces. The resulting correction to the speed of sound is small for low launch velocities; however, at 800 m/sec, the value of a_e obtained from Eq. (9) is 15% lower than the speed of sound obtained from direct differencing Eq. (3).

The variation in speed of sound with launch velocity obtained by this method is presented in Fig. 10. For launch velocities between 200 and 600 m/sec, the speed of sound of the propellant gas prior to shot ejection remains constant at 675 m/sec with a scatter of plus or minus 20 m/sec in the data. Subsequent to the 600 m/sec launch velocity, the propellant gas speed of sound begins to increase rapidly reaching a sonic value at a launch velocity of 780 m/sec. Further variations in the speed of sound with launch velocity may not be measured using the present technique.

The pressure measured at gage station 3 immediately after projectile passage is plotted as a function of launch velocity in Fig. 11. The muzzle pressure shows an almost linear variation with velocity until 600 m/sec when it increases suddenly. After the discontinuous jump, the pressure again increases

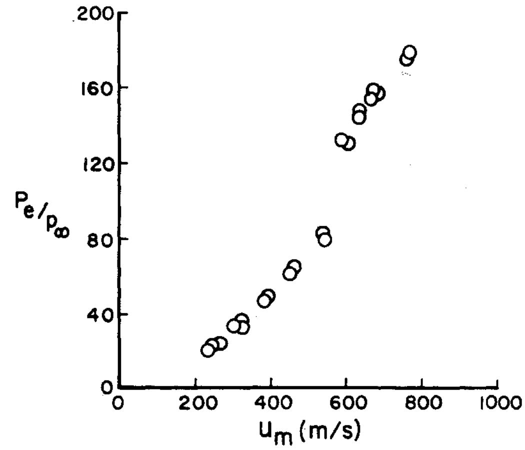

Fig. 11 Measured exit pressure.

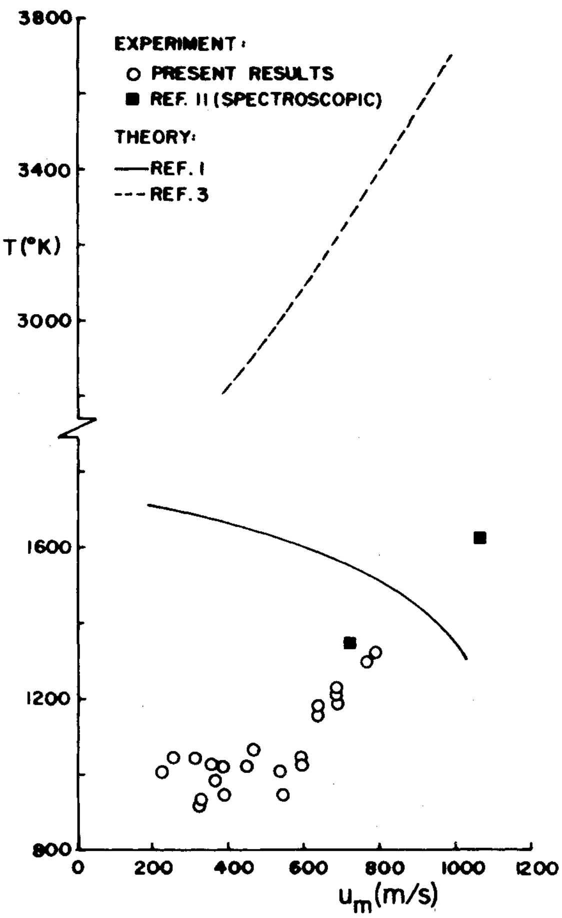

Fig. 12 Comparison between experimental and theoretical exit temperatures.

linearly. This sudden increase in muzzle pressure occurs at the same launch velocity at which the speed of sound begins to increase, thus, suggesting the possibility of a change in the combustion process. The design launch velocity of the round is 1000 m/sec. Lower velocities were obtained by simply removing propellant from the cartridge case without reducing the chamber volume. The propellant was held against the ignitor in the rear of the cartridge by a thin diaphragm. The free volume thus generated between the propellant bed and the base of the projectile may permit the establishment of pressure waves affecting the subsequent combustion history of the propellant.

The propellant gas temperature is computed from the measured sound speed by assuming the applicability of an equation of state. In the present case, it is assumed that by the time the propellant gases expand to the muzzle, they may be treated as an ideal gas. The muzzle temperature may be evaluated from

$$T = \frac{a^2}{\gamma R} \tag{10}$$

where[1] $\gamma = 1.25$, $R = 365.5\ \mathrm{m^2/sec^2\ K}$.

The temperature evaluated from the measured sound speed is shown in Fig. 12. At low launch velocities, the muzzle temperature remains roughly constant with a value of 1000 K. Subsequent to 600 m/sec, the temperature increases to a maximum value of 1320 K at 800 m/sec.

The present results do not agree with the predictions of typical interior ballistic models.[1,3] Baer and Frankle[1] use a lumped parameter technique that does not include gasdynamics. Although their predicted muzzle temperature level is near that of the measurements, the variation of temperature with increasing muzzle velocity is opposite to that of the current experiment. Celmins[3] applies the method of characteristics to solve the in-bore flow. He predicts muzzle temperature levels significantly higher than measured; however, his temperature variation with velocity is in accordance with the data trend. Also shown in Fig. 12 are the results of spectroscopic investigation of in-bore propellant gas temperature conducted by Klingenberg and Mach.[11] The two data points shown were obtained near the muzzle of two different 20-mm guns. Their data agree well with the present results, thereby reinforcing the disagreement with theory.

Conclusions

A procedure is developed that permits the determination of propellant gas temperature immediately behind the projectile at shot ejection. Pressure gages are used to observe the time of passage of the muzzle expansion at a known location. A differencing relation is presented to calculate the speed of sound of this wave. Incorporated in this relation are corrections to account for changes in speed of sound and flow velocity over the measurement period.

The procedure is used to determine the propellant gas temperature at the muzzle of a 20-mm gun over a range of launch velocities. Comparison of the measured temperature with representative interior ballistic models shows serious disagreement not only between theory and experiment, but also among the various theoretical approaches.

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