19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

MEASUREMENTS OF MUZZLE BRAKE EFFECTIVENESS

E. Schmidt

U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066, USA

The paper examines the analytic and theoretical work done on muzzle brakes over the past twenty years. The nature of the flow over the devices is considered and its implications on brake performance discussed. Correlations are presented between brake efficiency, blast overpressure, muzzle flash, and accuracy.

INTRODUCTION

Muzzle brakes, Fig. 1, are devices that act to recover momentum from the exhausting gun propellant gases. Interest in optimizing the performance of brakes has come and gone over the years. During World War II, considerable research was undertaken. As weapon calibers increased to counter more powerful tanks with heavier armor, recoil became a design problem. Germany[1,2] demonstrated an understanding of the muzzle gasdynamics and developed an amazing array of different brake variants, some of which were placed into production. In the United States, a major concern[3] centered on brake-like devices applied as blast deflectors. The goal was to reduce obscuration caused by debris lofted in the muzzle exhaust. After the war interest waned until in the seventies, when attack helicopters were fielded with muzzle brake equipped cannon. Interest centered[4,5] on blast overpressure on the aircraft surface particularly sections housing electronic components. In the eighties, blast[6–8] in the crew stations of towed howitzers became a concern. Presently, there is interest in lightweight fighting vehicles mounting high performance cannon. Recoil mitigation is a major consideration and provides a need to revisit previous efforts. This paper will give an overview of work to define the properties of open muzzle brakes, Fig.1, and their impact on the overall functionality of the weapon system.

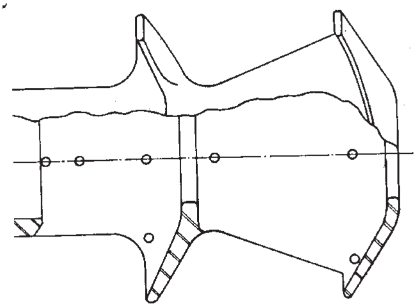

Figure 1. Open baffle muzzle brake.

The flow from guns has been studied extensively[9]. The high pressure propellant gases drive into the atmosphere displacing the surrounding air to form a strong blast wave which decays as it propagates away from the weapon. The propellant gas flow has the structure of a highly underexpanded supersonic jet. A property of the jet structure is that within the supersonic core, i.e., the region internal to the lateral shocks and Mach disc, the flow is quasi-steady. This means that the highly transient events occurring in the blast layer do not propagate beyond the jet shocks and property variations within the core are governed by the slower process of gun tube blow down. Since the muzzle brake functions largely within this core region, its treatment is simplified.

Oswatitsch[1] and Smith[10] both took advantage of the quasi-steady nature of the core flow to perform experiments on muzzle brake simulators immersed in steady jet flow. They define a brake efficiency factor

$$\beta = (T_{wo} - T_w)/T_{wo} \tag{1}$$

where T_w is the thrust with the brake installed and T_{wo} is the thrust without the brake installed. Since these were steady flow experiments, no projectile was launched.

Using what is in essence a ballistic pendulum, Pater[11] measured muzzle brake performance on an actual cannon. For this transient event, the brake efficiency factor was defined as

$$\beta = (I_{wo} - I_w)/(I_{wo} - m_p v_p) \tag{2}$$

where I_w is the impulse imparted to the free recoil device with the brake installed, I_{wo} is the impulse without the brake, and $m_p v_p$ is the muzzle momentum of the projectile. Thus, the term in the denominator is the total momentum available from the propellant gases. If the highly transient initial phase and the low momentum late time collapse of the core are neglected, Eq. (1) and (2) are essentially the same. This is the definition of brake efficiency used for the remainder of this paper. Subsequent sections will examine the variation of efficiency with brake geometry and consider the impact of efficiency on other brake properties, such as blast.

RECOIL ATTENUATION

Baur and Schmidt[6] used a free recoil device of Pater's design to measure the recoil attenuation characteristics of a variety of brake designs mounted on a 20 mm cannon. To permit rapid changes in geometry, axially symmetric configurations were employed where baffles were connected to the muzzle by a set of threaded rods. It was assumed that interference of the rods with the flow was small. Flat and angled baffles were examined, both singly and in pairs. To test the applicability of the axisymmetric data to an actual muzzle brakes, three-dimensional models were built for two of the designs (simulating the brakes on the M109 and M198 howitzers). Data were taken of the brake efficiency and blast overpressure. In addition, the muzzle flow field was observed using spark shadowgraphs.

For a single baffle moved along the line of fire, the brake efficiency first grows and then decays, Fig. 2. This behavior was observed and explained by Smith[10]. Near the muzzle, the lateral extent of the core flow is small and much of the momentum flux simply passes through the projectile hole in the baffle. As the device moves away from the muzzle, the lateral extent of the jet grows and more of the baffle is effective in turning the flow, thus recovering momentum. Eventually, the efficiency decays as the lateral extent of the jet becomes sufficiently large for momentum flux to pass around the outer edge of the baffle. The location of the peak[6] changes with brake geometry. For larger baffle geometries, the maxima is reached further from the muzzle. However, for all cases observed the growth and decay of efficiency was seen.

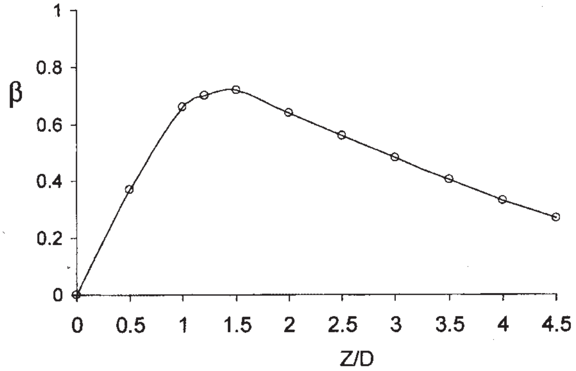

Figure 2. Variation in efficiency of single, axisymmetric baffle as it is moved away from the muzzle.

When a second baffle is added, some interesting behavior is observed, Fig. 3. The family of curves represents the variation of efficiency as the second baffle is moved away from the first. The changes are overlaid on data from Fig. 2. For example with the first baffle at z/D = 0.5, the total efficiency (for the two baffles) grows as the second baffle moves downstream. A maximum is reached when the second baffle is at z/D = 2.5. It is noted that the maximum double baffle efficiency does not follow from the optimal location for the single baffle; rather, it is attained when the first baffle z/D = 1.0 and the second baffle z/D = 3.5. The gain in performance for the second baffle is typically lower than that of the first (except for z/D = 0.5 where flow through the projectile hole is largely undisturbed) and occurs at a greater offset for the second baffle relative to the first than for the first relative to the muzzle. This behavior was noted by Oswatitsch[1] and ascribed to the loss of stagnation pressure as the flow is processed through the strong shocks developed by the first baffle.

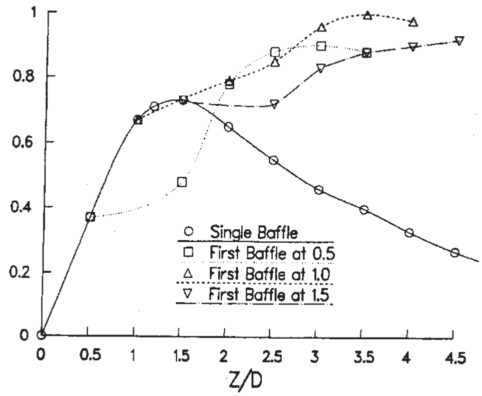

Figure 3. Variation of efficiency of two axisymmetric baffles as second baffle is moved relative to the first.

A related behavior can be observed as the weapon exit conditions change. A typical artillery piece is fired over a set of muzzle velocities (zones of fire) in order to provide accurate coverage of desired ranges. In firing the model M109 and M198 brakes, it was observed that as muzzle velocity changed, so did the brake efficiency, Fig. 4.

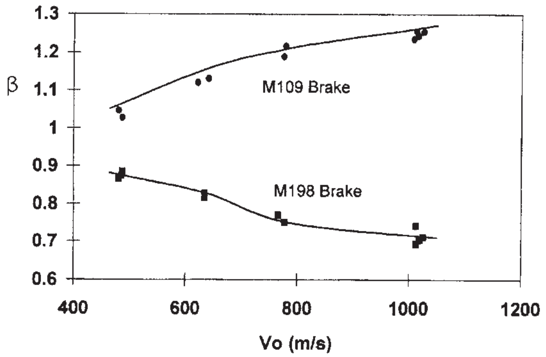

Figure 4. Variation of efficiency of model scale three-dimensional brakes with muzzle velocity.

The muzzle conditions at shot exit are presented in Table 1. The pressure is that after in-bore expansion to sonic conditions following projectile exit. As the muzzle velocity (and pressure) increase, the efficiency of both brakes change. However, the efficiency of the M109 model brake increases while that of the M198 decreases. The cause of this behavior is related to the geometry of the brakes relative to the flowfield. As muzzle pressure increases, the longitudinal and lateral extent of the supersonic core grow. Photographs[4] show the M198 baffle to be fully immersed in the supersonic core before the 460 m/s case. At higher velocities, the core grows past the baffle. When this occurs, momentum flux passes beyond the outer edge of the baffle and efficiency drops. For the M109 baffle, a different behavior is observed. This is a relatively large baffle and is swept back toward the muzzle. As velocity increases, the baffle becomes more fully immersed in the supersonic core, interdicting more of the momentum flux. By 615 m/s, the core moves to the edge of the baffle and it would be expected that the efficiency would begin to decrease. This was not observed in the data and is thought to be associated with the processes occurring on the second baffle of the double baffle brake. Obviously, the flow is not as simple as described in this paragraph; however, it is felt that the explanations reflect the basic phenomenology of the process.

V_p (m/s)	280	463	615	775	1050
T^* (K)	875	933	1052	1320	1705
P^*/P_∞	14	45	101	189	287

Table 1. Muzzle exit conditions (20 mm cannon)

BLAST OVERPRESSURE AND FLASH

In diverting the propellant gases to recover momentum, the muzzle brake alters the directional nature of energy deposition and through this the blast overpressure field. The variation in blast strength with angle away along a constant radius arc[6] is shown in Fig. 5. For the bare muzzle, the blast is quite strong ahead of the gun, i.e., the axis along which the gases exhaust. With each of the brakes, the peak pressure moves toward the rear of the gun reflecting both the brake efficiency and the baffle sweep angles. This property of muzzle brakes is well known by gun crews stationed behind the weapon.

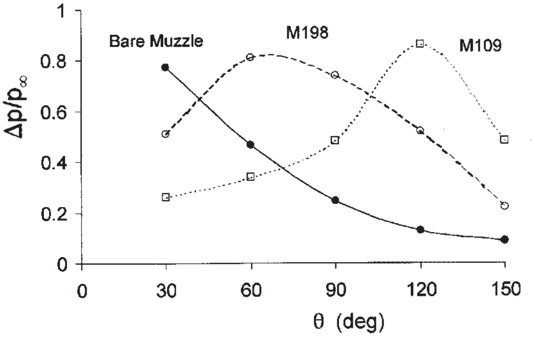

Figure 5. Variation in peak blast overpressure with angle relative to the line of fire for the bare muzzle and M198 and M109 three-dimensional brakes.

From the 20 mm data for the set of muzzle brakes tested, Baur and Schmidt define a correlation between overpressure with and without a brake in place

$$(p_w - p_\infty)/\, p_\infty = [p_{wo} - p_\infty)/\, p_\infty][1 + \beta(0.8 \; - 1.5\cos\theta] \qquad (3)$$

where θ is the angle from the line of fire (zero is forward), p_W, p_{WO} are the peak pressures behind the blast wave, and p_∞ is the ambient pressure. This expression is reasonably accurate for directions fore and aft of the line of fire; however, laterally, it does not accurately predict the blast field. In part this is due to a failure to account for the details of baffle geometry, both in terms of baffle sweep angle and the three-dimensional nature of real brakes (i.e., with upper and lower attachment plates). Fortuitously, in the vicinity of the crew both the axially symmetric and three-dimensional overpressures converge.

There are some techniques that can be used to reduce the blast overpressure while still maintaining brake efficiency. For multi-baffle brakes, it has been observed[6] that magnitude of blast is dominated by the characteristics of the first baffle; thus, it is of interest to examine the blast overpressure variation with position of the first baffle, Fig. 6. The plot shows the variation of efficiency and overpressure, both normalized to their respective peak values, as the baffle position is changed. The overpressure data is taken on the 150° ray at a radial separation of r/D = 30 from the muzzle. It is seen that the overpressure increases along with the brake efficiency, but peaks at z/D = 1 while efficiency peaks at z/D = 1.5. At the location of maximum brake efficiency, the overpressure has dropped by 20% relative to its peak value. This behavior was also observed for other brake designs. The baffle tested was the same as that used in Fig. 3 and 4. Since the blast overpressure with two baffles was only slightly greater than with the single baffle case, it can be hypothesized that the best configuration would be one where the first baffle is located close to the muzzle (e.g., z/D = 0.5, Fig. 4) and the second baffle placed near the peak efficiency point (e.g., z/D = 2.5). This provides a smaller blast overpressure in the crew area, a high level of efficiency, and a relatively compact device.

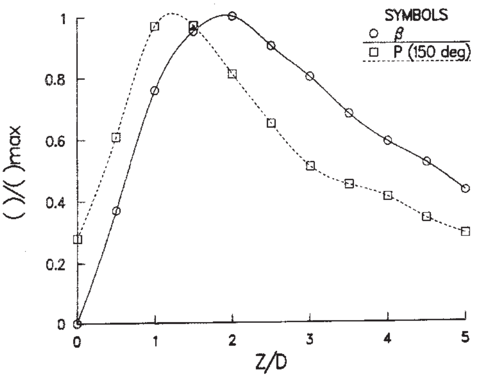

Figure 6. Variation of efficiency and peak overpressure (both normalized to local maxima) along 150° ray with location for a single axisymmetric baffle.

In addition to increasing overpressure behind the weapon, the presence of a muzzle brake can act to increase the probability of flash. It is well known[12] if there is a proper mixture between propellant gas and air with sufficiently high temperature over a reasonable induction period, ignition may take place. The luminous region produced by such combustion has significant brightness and extent. It is called secondary flash. For high performance tank guns, secondary flash almost always occurs. Flash suppressants such as potassium sulfate are employed to reduce the probability of flash in artillery. However, the use of muzzle brakes can have the opposite effect. The baffle surfaces of muzzle brakes cause strong shock waves to form in the exhaust flow. Passage through a series of internal shocks followed by a final Mach disc can significantly heat the propellant gases. A highly idealized approximation of this flow shows[8] the influence of the shock heating, Fig. 9. The plot shows the mixture temperature versus the mixture ratio where r = 0 is pure propellant gas and r = 1 is pure air. The double baffle brake significantly raises the mixture temperature when compared to the bare muzzle case. The dashed lines show empirical ignition criteria[13] for different percentages of flash suppressant. In fact, tests showed that the howitzer in question did flash. While bare muzzle tests were not conducted to show an absence of flash, the model was applied to each zone of fire with the brake in place and produced reasonable agreement with data.

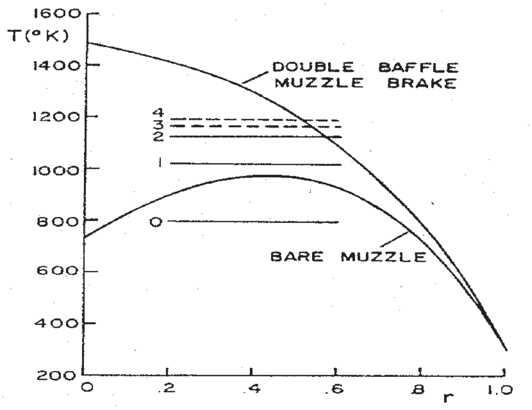

Figure 7. Effect of a muzzle brake on air/propellant gas mixture temperature (horizontal lines show ignition threshold for different percentages of flash suppressant).

CONCLUSIONS

The use of muzzle brakes may be necessary to reduce recoil of high performance cannon on future lightweight fighting vehicles. There is a significant body of experimental data describing the muzzle brake gasdynamics which points out some of the pitfalls associated attempts to optimization of brake performance. While not discussed in this paper, there have been a number of numerical studies of muzzle flow both axially symmetric[14] and fully three-dimensional[15]. The work of Carofano uses the most advanced numerical scheme and produces impressive results. Given the advances in these techniques, it would be worth applying modern computational fluid dynamics to predict the complete properties associated with any new family of muzzle brakes being considered. Such an approach would greatly improve the understanding of the flow internal and external to the devices and would aid in optimizing their performance.

REFERENCES

1. K. Ostwatisch, "Flow Research to Improve the Efficiency of Muzzle Brakes," R1001, *Army Ordnance, Goettingen*, GE, Oct 1944.
2. E. Hammer, "Muzzle Brakes, Volume 1, History and Design," TR1-1000L, *The Franklin Institute, Philadelphia,* PA, Jun 1949 (AD111481).
3. E. Hammer, "Anti-Obscuration Devices and Muzzle Brakes," PN 1750-3, *The Franklin Institute, Philadelphia*, PA, Apr 1948 (AD71819).
4. E. Gion and E. Schmidt, "Measurements on a Circular Plate Immersed in Muzzle Flow," MR2762, *Ballistic Research Laboratory, APG, MD,* Jun 1977.
5. E. Schmidt, E. Baur and W. Thompson, "Comparison of the Performance of Candidate Muzzle Devices for 30 mm Cannon," MR03337, *Ballistic Research Laboratory, APG, MD,* Feb 1984.
6. E. Baur and E. Schmidt, "Relationship Between Efficiency and Blast from Gasdynamic Recoil Brakes," Paper 85-1718, AIAA, Jul 1985.
7. R. Dillon, "A Parametric Study of Perforated Muzzle Brakes," ARLCB-TR-84015, *Benet Weapons Laboratory, Watervliet, NY,* May 1984.
8. E. Schmidt, "Secondary Combustion in Gun Exhaust Flows," ARO R82-1, *Transactions of the 27th Conference of Army Mathematicians,* 1982.
9. **Gun Muzzle Blast and Flash,** *AIAA Progress in Astronautics and Aeronautics, Vol. 139,* 1992.
10. F. Smith, "Model Experiments on Muzzle Brakes," R2/66, *RARDE, FT Halstead, UK,* Jun 1966 (AD487121).
11. L. Pater, "Scaling of Muzzle Brake Performance and Blast Field," TR3049, *Naval Weapons Laboratory, Dahlgren,* VA, Oct. 1974.
12. G. Klingenberg and H. Mach, "Investigation of Combustion Phenomena Associated with the Flow of Hot Propellant Gases," *Combustion and Flame, Vol. 27,* 163–176, 1976.
13. G. Carfagno, **Handbook on Gun Flash,** *Franklin Institute, Philadelphia, PA,* 1961.
14. G. Carofano, "A Note on the Blast Signature of a Cannon," ARCCB-TR-92014, *Benet Weapons Laboratory, Watervliet, NY,* Mar 1992.
15. J. Buell and G. Widhopf, "Three-Dimensional Simulation of Muzzle Brake Flowfields," Paper 84–1641, AIAA, 1984.