Multidimensional Interior Ballistic Two-Phase Flow and the Chambrage Problem

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The effect of the chamber geometry of tube weapons on the performance and on the interior ballistic two-phase flow is investigated by applying the two-dimensional axisymmetric model of interior ballistics (AMI). The axisymmetric formulation in AMI has been modified such that arbitrary chamber shapes can be considered without any simplifying assumptions. The numerical results for large caliber systems show interesting flow patterns caused by the axial changes in cross section, e.g., by the transition cone or the ignitor geometry. The numerical procedure is explained. Computational results emphasize the differences between a constant-diameter chamber-bore configuration and a configuration with chambrage, i.e., with nonconstant diameter.

Nomenclature

A = cross section of the chamber or tube of a gun
g = determinant of the Jacobian
m_c = initial propellant mass
m_P = projectile mass
$\bar{p}$ = volume-averaged mean gas pressure
p_P = gas pressure at the projectile base
Q = gas production rate per time and volume unit by propellant and ignitor
s = distance between breech and projectile base
$\dot{s}$ = projectile velocity
u,v = axial and radial velocity components in the physical space
x,y = axial and radial coordinates in the physical space
α = porosity, ratio of the gas volume to the total volume
ρ = gas density
ξ, η = Cartesian coordinates in the computational space

Introduction

A GUN is called a chambered gun, or a gun with chambrage,[1] if the diameter of the chamber differs from the diameter of the barrel (cf. Fig. 1). When the chamber diameter is equal to that of the barrel, the gun is described as a constant-diameter gun. Actually, all conventional types of tube weapons are chambered, caused by the transition cone, by interior components of the charge, e.g., the ignitor, and/or by the inner shape of the main chamber, in our example a cone. Future large-caliber, high-performance guns may have a strong chambrage eventually because of design and performance reasons.

The effect of the chambrage on the multidimensional interior ballistic two-phase flow has not been investigated systematically yet either by experiment or by computation. Therefore, it is not known how the chambrage impacts the performance as well as the two-phase flow pattern. On the other hand, interior ballistics models frequently make use of simplifications of the chamber geometry assuming a constant-diameter gun. Only two- and three-dimensional models can have the capability to include properly the chambrage. In general, lumped-parameter models do not take account of the chambrage. By comparing the computational results of a one-dimensional gas-dynamic model for a chambered gun with those of a lumped-parameter model using the same inputs, Robbins et al.[2] found, for the charge-to-projectile mass ratios of 1 and 4, differences in muzzle velocity of 5 and 10%, respectively, and in maximum breech pressure of 10 and 30%, respectively. These differences were reduced substantially by modifying the lumped-parameter model with a correction for the chambrage. The results computed with the one-dimensional gas-dynamic model with and without chambrage show that, for all mass ratios considered (0.25, 1, 4), the muzzle velocity and the maximum breech pressure are lower for the case of chambrage. The differences increase with increasing mass ratio.

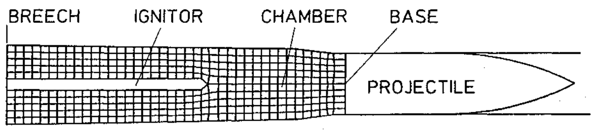

Fig. 1 Typical geometry of a chambered gun.

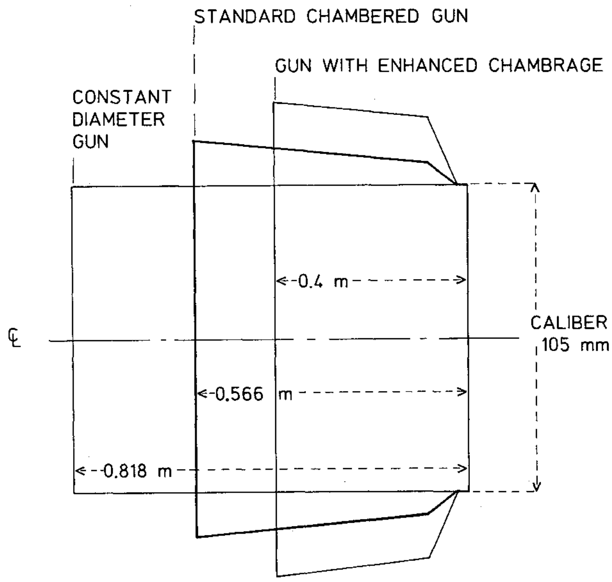

Fig. 2 Chamber geometries of equal volume.

Presented as Paper 89-2556 at the AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA, July 10-12, 1989; received Oct. 10, 1989; revision received March 3, 1990; accepted for publication March 8, 1990. Copyright © 1990 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved.

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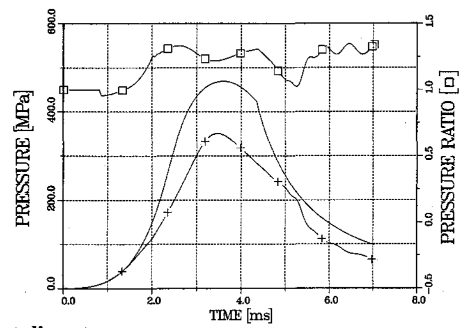
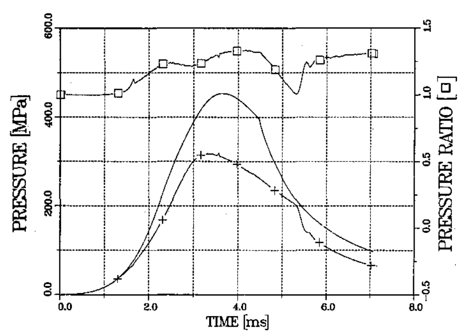
Apparently, these results are in contradiction to Seigel's study[1] where he investigated how the chambrage affects the performance. He summarizes that the projectile velocity in the initial stages of motion increases with increasing chambrage for a constant mass ratio, but in the latter stages the projectile velocities will be approximately the same for all kinds of chambrage. However, to understand these statements, one has to keep in mind that these results hold only for preburned propellant (PP) guns and therefore may not contradict the behavior of real guns. In a PP gun, the propellant has completely turned into gas, i.e., the gas pressure reaches its peak value before the projectile starts moving. This assumption is not true for a real gun. The unsteady feedback between rate of burning, state of gas, chambrage, and wave propagation causes the propellant to burn more slowly for increasing chambrage and dominates the interior ballistic cycle, which is different from the simple expansion flow in a PP gun.

The stream-tube formulation applied in one-dimensional gas-dynamic models allows the inclusion of the chambrage as axial moderate changes in the cross section as long as the fractional rate of change of cross section A with respect to distance along the axis x is supposed to be small, namely $dA/A\,dx \ll 1$. This condition may not be satisfied in interior ballistics, e.g., for novel regenerative liquid-propulsion systems. The one-dimensional formulation does not give any resolution in the radial direction. As will be shown later, the transition region between the chamber and the tube in a chambered gun causes radially directed accelerations of the gas and of the propellant grains as well as other spatial effects. Therefore, a two-dimensional or, even better, a three-dimensional formulation of the chambrage problem is necessary to get a complete resolution of the chambrage-dependent phenomena.

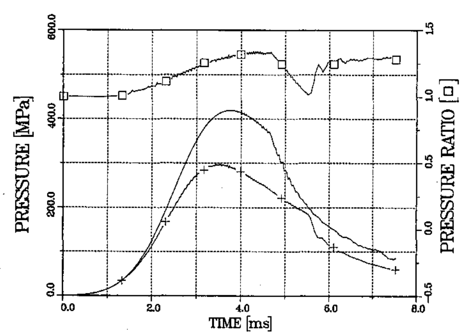
The model we are applying is an axisymmetric model of the interior ballistics (AMI), a two-dimensional formulation for rotational symmetry, now modified in order to describe the chambrage or, even more generally, each kind of real geometry of the interior ballistics flow and reaction region consisting of the chamber, ignitor, transition region, projectile base with arbitrary shape, and tube. The AMI code is supposed to give more realistic results of the chambrage effects than can be expected by one-dimensional or lumped-parameter models. In the sequel, both the code and the handling of the geometry problem are explained. Computational results will show the differences between a constant diameter and a chambered gun as well as interesting features of the flow pattern in the chambered gun.



a) Constant diameter gun



b) Standard chambered gun



c) Gun with enhanced chambrage

Fig. 3 Breech pressure (–), projectile base pressure (– + –), and pressure ratio (– □ –) for idealized ignition.

Structure of the AMI Model

The complete numerical solution of the chambrage problem is addressed by means of the AMI model. This interior ballistics model has been jointly developed by the Ernst-Mach-Institut (EMI) and the Franco-German Research Institute (ISL) for a constant-diameter gun.[3,4] For this simplified geometry, the model has been verified.[5] The basic features are summarized in the following. AMI describes the two-phase flow in a conventional type of tube weapon for a rotationally symmetrical geometry of the flow region between breech and projectile base.[6] The propellant gas assumed to be compressible is the first phase, whereas the second phase represents the solid propellant assumed to be incompressible. The two phases interact with each other by mass exchange via combustion, momentum exchange, and heat release caused by the combustion of the propellant.

At present, the ignition system is included by source terms either in the basic equations for mass, momentum, and energy[5] or as boundary conditions at the ignitor tube. The production rate of the sources depends on the geometric and chemical characteristics of the ignitor. The modeling of the ignition of a charge considers the heat transfer from the hot ignitor gases to the cold propellant and the heat conduction into the propellant.[4] The numerical solution of the Eulerian type of two-phase equations for the constant diameter as well as chambered gun is based on MacCormack's explicit finite-difference scheme.[10]

Numerical Technique to Solve the Chambrage Problem

The flow region is initially equal to the weapon chamber, which may be chambered and may have parts intruding from the breech (ignitor) or projectile base (fins) (cf. Fig. 1). This holds for the initial stage of the interior ballistic cycle, until the projectile starts moving. From then onwards, the flow region will develop with the projectile motion. The portion of the barrel behind the projectile grows. The flow volume to be added in any time step to the flow region increases with the projectile velocity.

The interior ballistic code AMI addresses axisymmetric flows. The physical domain therefore can be specified in cylindrical coordinates independent of angular position with coordinate x pointing in the axial direction and y pointing in the radial direction. Any grid that covers the flow region has to be stretched during the shot development time. All calculations are performed on a fixed rectangular grid with constant mesh size. To solve a problem with time-varying geometry given in physical space, at any time we have to transform the actual flow region into the computational space with the Cartesian coordinates ξ and η. Depending on the transformation used, the line in physical space corresponding to a coordinate line

$\xi = \text{const}$ and $\eta = \text{const}$ may be curved. In practice, we have to find the meshpoints of a general grid that covers the flow region and is adjusted to its shape. These points in physical space, which transform into the grid points in computational space, are determined by a grid generator.

The flow problem to be solved consists of a set of balance equations, forming a system of partial differential equations. To illustrate how these equations change with a coordinate transformation, we will show the continuity equation for the gas phase as an example. The continuity equation expressed in physical coordinates is

$$\frac{\partial}{\partial t}(\alpha\rho) + \frac{\partial}{\partial x}(\alpha\rho u) + \frac{1}{y}\frac{\partial}{\partial y}(y\alpha\rho v) = Q \tag{1}$$

In order to do the flowfield calculation in curvilinear coordinates, we have to use the correct coordinate representation of the balance equations of our problem. Dependent on the transformation used, the equations may become substantially more complicated by additional terms.

The early version of the AMI code assumed a cylindrical chamber, equal in diameter to the caliber of the weapon. A linear axial transformation with the flow region length s was sufficient to get the computational grid; the transformation terms occurring in the equations in the computational space were simple in nature. The projectile velocity enters the equation as $\dot{s}$ and Eq. (1) changes to

$$\frac{\partial}{\partial t}(s\alpha\rho) + \frac{\partial}{\partial \xi}(\alpha\rho u - \alpha\rho\xi\dot{s}) + \frac{1}{y}\frac{\partial}{\partial \eta}(sy\alpha\rho v) = sQ \tag{2}$$

with $y = \eta$. For problems with arbitrary chamber geometry, a fully general grid generator, namely a partial linear differential equation of the Poisson type, is used.[7] Data on the border of the flow region specify the Dirichlet boundary-value problem to be solved for interior points. The grid generator produces a generally orthogonal grid using the weak constraint method that determines the right side of the Poisson equations in an iterative manner.

The transformation from physical coordinates x and y to the coordinates ξ and η in computational space at any point is characterized by the Jacobian determinant $g = x_\xi y_\eta - x_\eta y_\xi$. The partial derivatives are computed numerically and have to be recalculated at any time step in which the generation of a new general grid is needed because of flow-region development. Any grid point in the physical space has its grid velocity $(\partial x/\partial t, \partial y/\partial t)$ due to the expansion of the flowfield, which is calculated from two subsequent grid point positions. Equation (1) then becomes

$$\frac{\partial}{\partial t}(\alpha\rho) + \frac{1}{\sqrt{g}}\left\{\left(\frac{\partial x}{\partial t}\right)\left[y_\xi\frac{\partial(\alpha\rho)}{\partial\eta} - y_\eta\frac{\partial(\alpha\rho)}{\partial\xi}\right] + \left(\frac{\partial y}{\partial t}\right)\left[x_\eta\frac{\partial(\alpha\rho)}{\partial\xi} - x_\xi\frac{\partial(\alpha\rho)}{\partial\eta}\right] + \left[y_\eta\frac{\partial(\alpha\rho u)}{\partial\xi} - y_\xi\frac{\partial(\alpha\rho u)}{\partial\eta}\right] + \frac{1}{y}\left[x_\xi\frac{\partial(y\alpha\rho v)}{\partial\eta} - x_\eta\frac{\partial(y\alpha\rho v)}{\partial\xi}\right]\right\} = Q \tag{3}$$

This equation shows the typical form of a balance equation after the coordinate transformation. The solution of the transformed equations is done with MacCormack's explicit finite-difference scheme.[10]

Computational Results

The two-dimensional AMI code, now adapted to handle chamber geometries differing from the cylindrical shape, allows for the study of the spatial effects caused by the chambrage. First, we compare the constant-diameter geometry as a reference both with a real chambered weapon geometry of a 105-mm tank gun widened 31% with respect to the caliber and

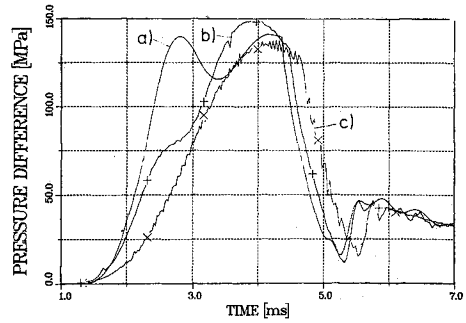


Fig. 4 The pressure difference between breech and base for idealized ignition: a) constant diameter gun, b) standard chambered gun, and c) gun with enhanced chambrage.

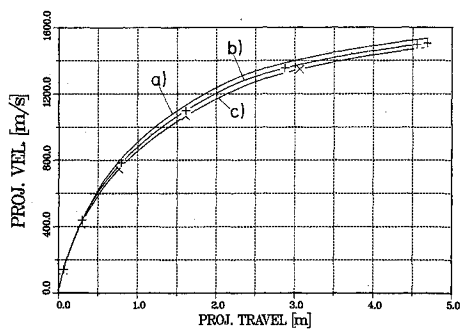


Fig. 5 Influence of the chambrage on the projectile velocity for idealized ignition: a) constant diameter gun, b) standard chambered gun, and c) gun with enhanced chambrage.

some fictitious enhanced chambrage of 54%. All test cases are designed to have the same chamber volume, charge, and projectile mass. The charge-to-projectile mass ratio is 0.925 and the propellant is of an M30 type. The chamber length decreases with chambrage. For the constant-diameter weapon, it is 81.8 cm, 145% of the standard chambered weapon chamber length of 56.6 cm; and for the weapon with enhanced chambrage, the length is 40.0 cm, 70% of the standard weapon chamber length (cf. Fig. 2).

In the first stage of our investigation, we consider a simplified ignition process. From the beginning, the total charge is supposed to burn; no ignitor action is needed. Figure 3 shows how the chambrage affects the time-dependent development of the gas pressure. All three plots contain the pressure at the breech and at the projectile base (+). In addition, the ratio (□) of the volume average of the pressure $\bar{p}$ in the flow region and the projectile base pressure p_p shows the spatial situation in comparison with the so-called Lagrange gradient,[2] given by the ratio $\bar{p}/p_p = 1 + m_c/3m_p$ constant in time, as it is used in lumped-parameter models. The Lagrange gradient is a simplifying assumption in order to get a relation between the spatial mean pressure and the pressure at the projectile base assuming a linear gas velocity profile between the breech and the projectile base. In our case, the Lagrange gradient value is 1.308. The three quantities in Fig. 3 reflect the influence of the chambrage on the ballistic flow problem. Increasing chambrage lowers the maximum pressure, and some shift in time indicates slower burning of the charge and later burnout. Since the longitudinal extension of the total flowfield decreases with increasing chambrage, the rarefaction waves initiated by the projectile motion need a shorter time to run through the flow region for the increasing chambrage. This means the gas pressure is lowered earlier. Lower gas pressure causes lower gas production by burning. Therefore, the maximum pressure decreases as well as the time period of the propellant combustion increases. The burnout of the propellant can be detected as a bench of the pressure curves. After burnout, the pressure ratios approximate the Lagrange gradient. The shapes of the time-dependent ratios show a similar character as in Figs. 2 and 8 of Robbins et al.,[2] where the mass ratio is 1.0. The deviations may be caused by the more realistic spatial description of the chambrage compared to the one-dimensional description.[2] The difference of breech and base pressure is depicted for the three chamber geometries in Fig. 4. With increasing values of chambrage, the muzzle velocity drops (cf. Fig. 5). In our example, the variation in muzzle velocity is 3%.

The assumption of the simplified ignition produces the limiting case of a one-dimensional flow in the case of a constant-diameter gun. All two-dimensional effects observed in the chambered guns are initiated by the changes in geometry. In the constant-diameter gun, there are no radial flow components; the flow variables do not vary across the tube diameter. Since, in a chambered gun, conical chamber portions form a nozzle, the flow is choked ahead of the nozzle and accelerated in the nozzle. The flow then enters the gun tube and pushes the projectile ahead.[9]

In addition, we looked at the chamber geometry in which the volume filled by the center core ignitor is left out but still simplified ignition is assumed. Figure 6 shows vector plots of both the gas and propellant grain velocities for the standard chambrage shortly after shot release. They confirm that the two phases move differently. The radial velocity component must be in accordance with the wall slope and therefore is mainly negative, i.e., it is directed towards the centerline. The interaction of gas and propellant is visible on the plots of the porosity. The distribution of the porosity points at several regions of accumulation and of dispersion of the propellant. In order to clarify the spatial resolution, there are two views of the porosity. The horizontal projection in conjunction with the distribution of the grid lines allows the identification of the

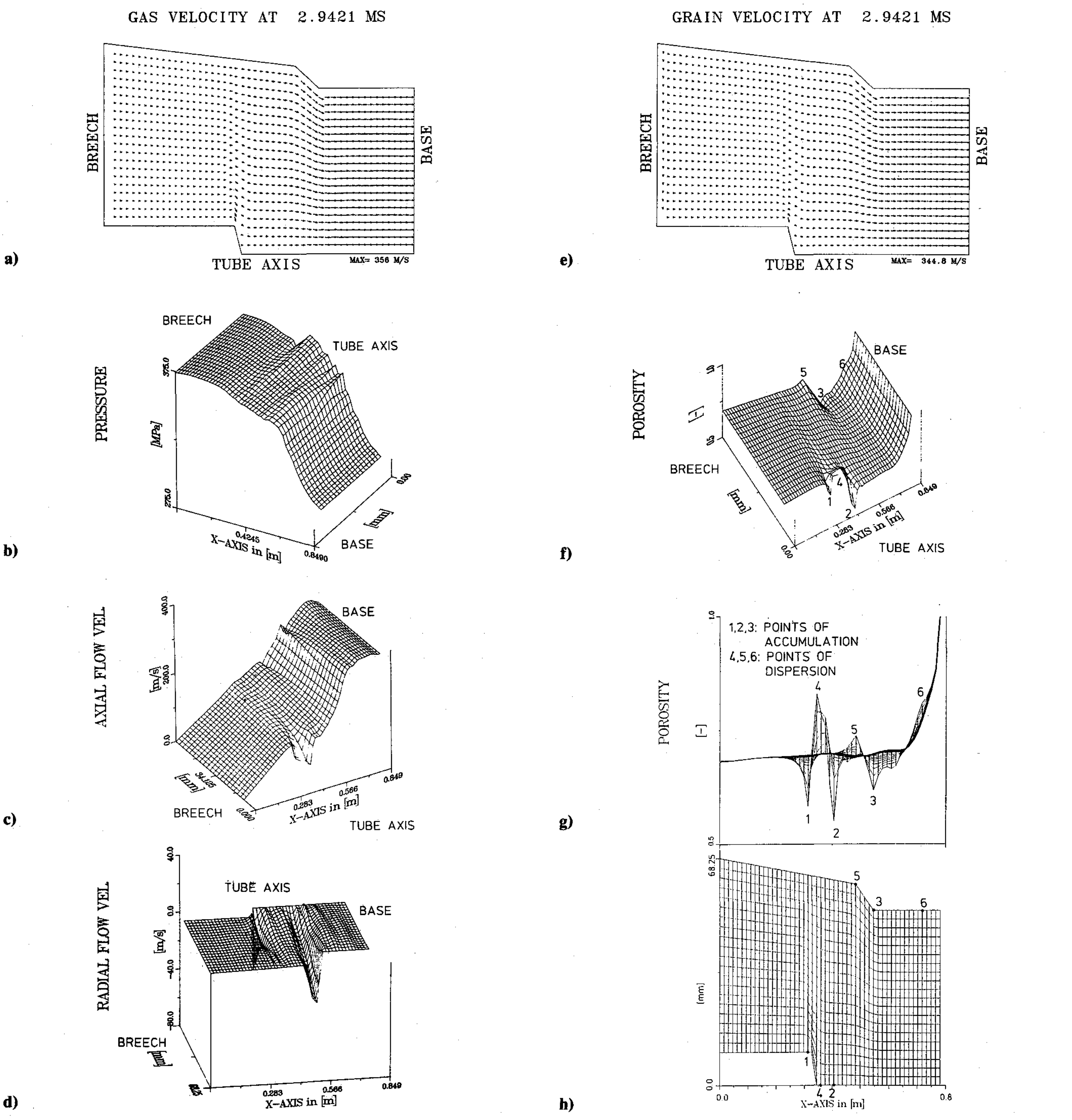


Fig. 6 Standard chambered gun, ignitor volume left out, for idealized ignition (time 2.94 ms; projectile velocity 345 m/s).

location of the extrema in porosity. The gas flow, accelerated in the transition cone, in the outlet region turns outwards into the zone of lower propellant concentration, and further accelerates into this zone and overshoots the centerline velocity. The effect of the chambrage on gas pressure in this situation is also shown in Fig. 6. The transition cone causes a plâteau in the chamber due to the choking. The pressure drops in the outlet region. At all times during the interior ballistic cycle, the positions of change in chamber wall slope are sources of additional disturbances not existent in the constant-diameter gun, which travel up and downstream. All observed effects are more pronounced for a higher value of chambrage.

The real interior ballistic charge, however, is ignited by an ignitor that produces hot gas and hot particles at particular locations. At present, hot particles are neglected. In our example, based on a real system, the ignitor is supposed to blow out gas through the boundary at the upper two-thirds of the ignitor tube. This fact becomes obvious in the early distributions of the gas pressure, the intergranular stress, the gas and grain velocities, and the porosity (Figs. 7–9). In total, the structure of the ignitor-driven flow looks very different from the flow pattern of the case where simplified ignition was assumed, e.g., in Fig. 6. Above all, the Lagrange gradient is meaningless for the early time period since the spatial spreading of the gas pressure does not agree with the Lagrangian assumption of a monotonic pressure distribution between breech and projectile base.[8]

Figures 7–9 show the spatial distribution of some important quantities at two times. At the first moment at 0.228 ms, the activity of the ignitor blowing mainly in radial direction dom-

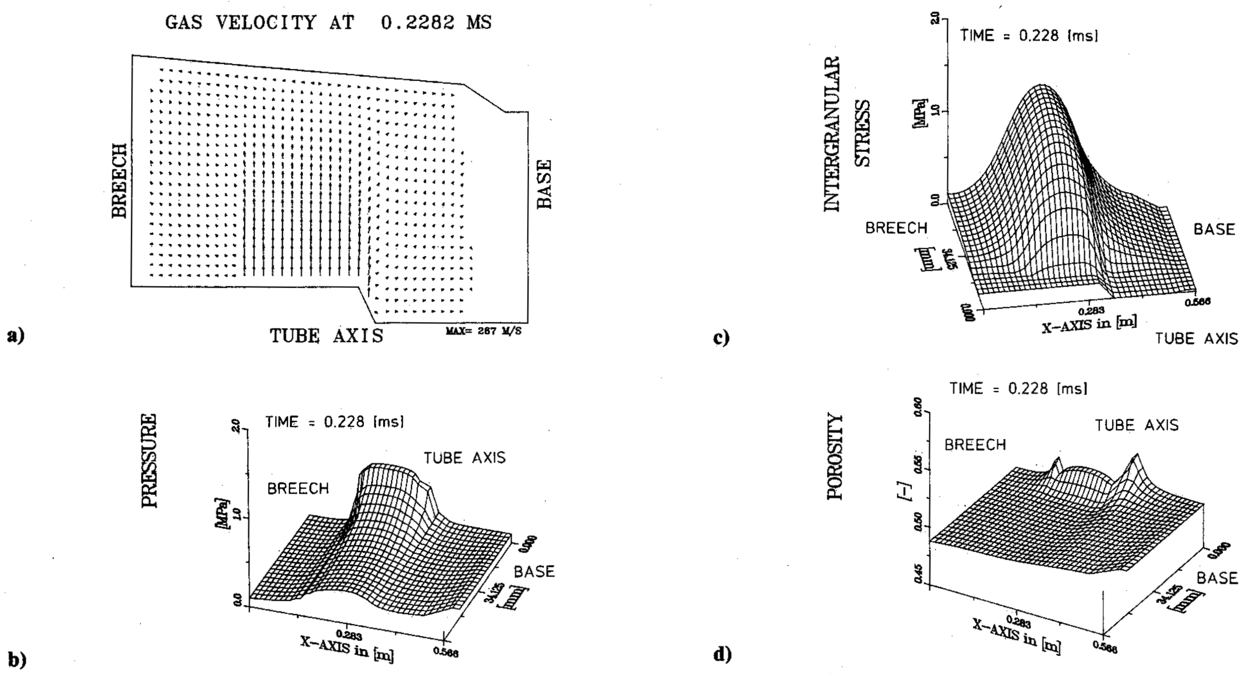


Fig. 7 Standard chambered gun with center core ignitor (time 0.228 ms, ignitor blowing).

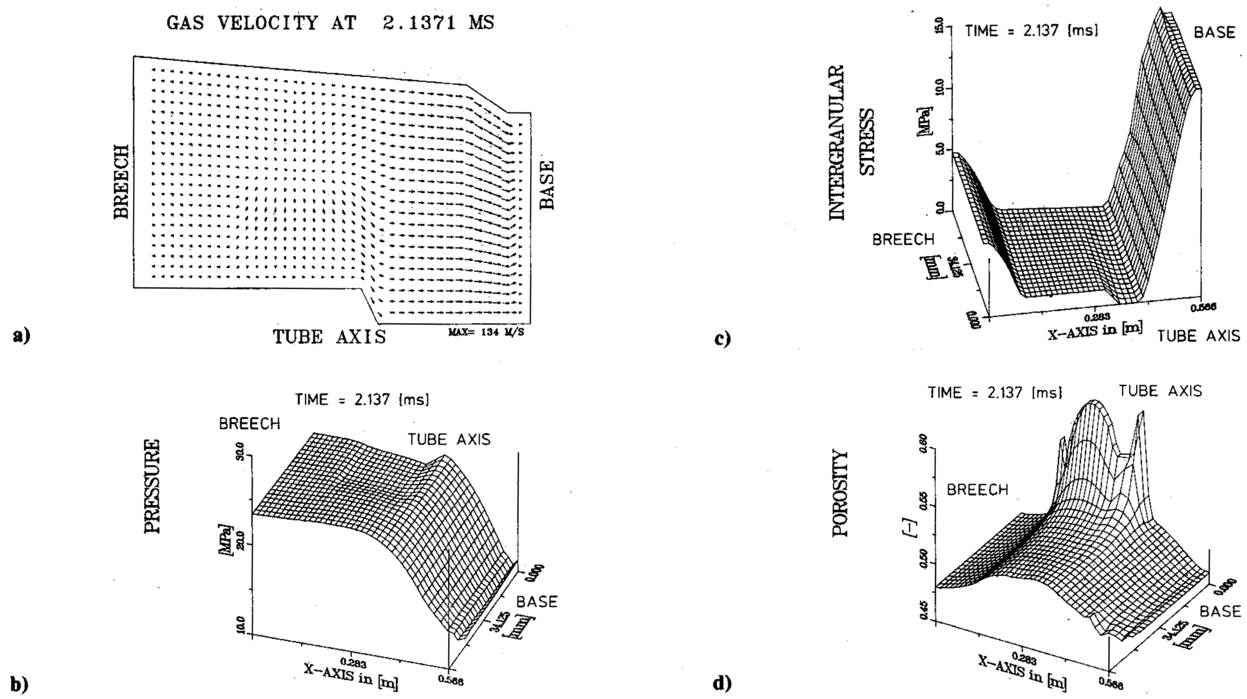


Fig. 8 Standard chambered gun with center core ignitor (time 2.137 ms, ignitor stopped blowing, begin of projectile motion).

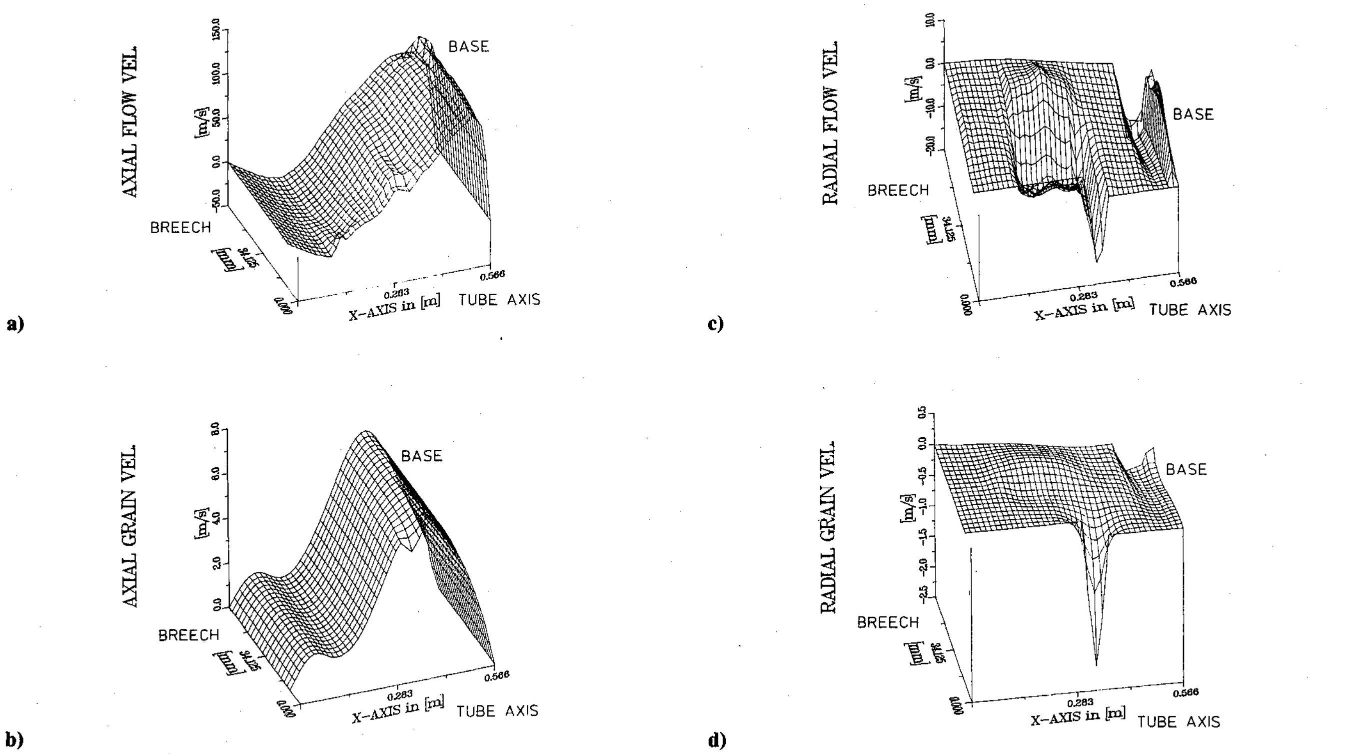


Fig. 9 Comparative view of gas and grain velocity components (time 2.137 ms, ignitor stopped blowing, begin of projectile motion).

inates the flow pattern (Fig. 7). The propellant is moved radially towards the chamber wall by the radially directed gas flow. As a consequence, the intergranular stress builds up with a maximum value at the chamber wall. The total charge is ignited approximately at 2.137 ms, which also agrees with the projectile start (Fig. 8). At this time, the ignitor has stopped to blow. Therefore, the main flow direction is axially disturbed by the typical chambrage influence and by the radial flow back into the region where initially the ignitor pushed away parts of the charge. The intergranular stress concentrates at the breech and at the projectile base with an absolute maximum at the projectile base. This behavior has been verified experimentally.[5] Figure 9 shows the spatial distribution of the flow velocities such that a better quantitative evaluation can be achieved.

Conclusions

The application of the two-dimensional, two-phase code AMI shows that the variation of the chambrage affects the interior ballistics cycle. By varying the chambrage geometry only, we found that the maximum pressure drops as well as the projectile velocity with increasing chambrage for both cases of ignition considered. The simplifying assumption of a constant-diameter gun as it is common for several models for simulating a chambered gun is not allowed, above all if the reaction of the charge depends sensitively on the ignition. A proper adaption of the ignition device to the simplified chamber geometry does not seem to be possible for propellant-ignitor configurations as considered here. This argument is mainly based on the intergranular stress. Its development in space and time is strongly affected with drastic change in peak values,[8] by the ignitor position in conjunction with the chambered geometry and the blowing characteristics. However, it is of minor importance whether the ignitor is assumed to be a part of the two-phase flow region or is handled as a boundary.

Acknowledgment

The authors would like to thank K. Wolf for writing the graphics software used to display the computational results. They would also like to thank E. Messner.

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