Steady Deflagration Structure in Two-Phase Granular Propellants

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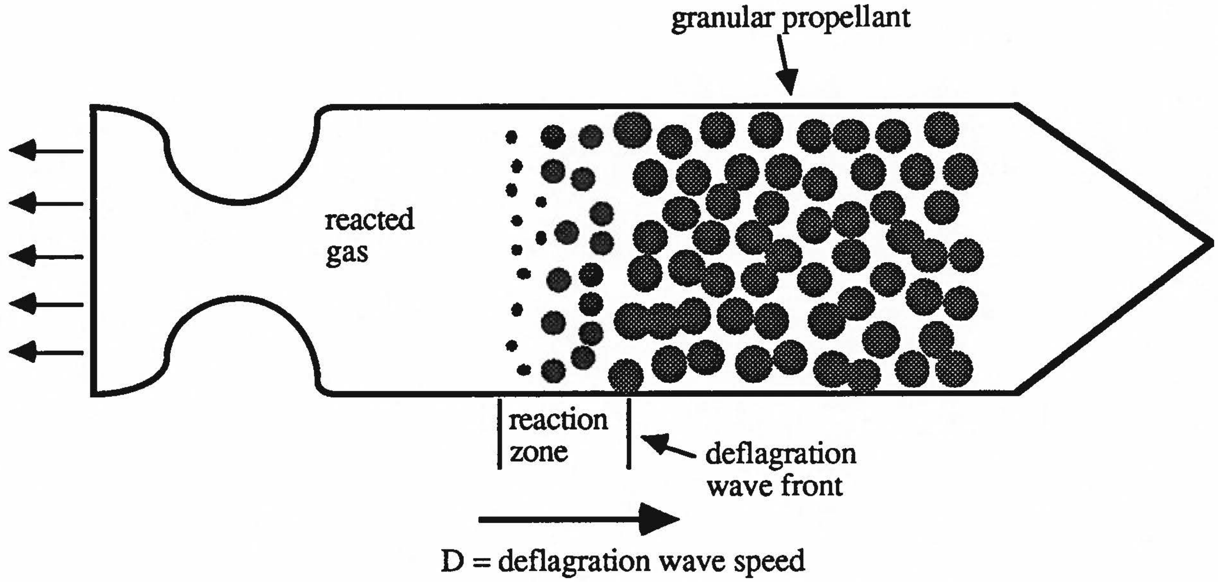
Envisioned Two-Phase Deflagration



Review of Two-Phase Deflagration

1973--Kuo, Vichnevetsky, and Summerfield, AIAA Journal

1974--Kuo and Summerfield, AIAA Journal

1975--Kuo and Summerfield, 15th Combustion Symposium

1986--Drew, Combustion, Science and Technology

Related Work

1986--Baer and Nunziato, International Journal of Multiphase Flow

1988--Powers, Stewart, and Krier, Dynamics of Explosions, AIAA Progress

1989--Powers, Stewart, and Krier, Journal of Applied Mechanics

1989--Powers, Stewart, and Krier, Combustion and Flame

Model Features

-Representative of a larger class of two-phase models

-Each phase obeys a mass, momentum, and energy evolution equation

-Mixture mass, momentum, and energy conserved

-Volume fraction ($\phi \equiv$ phase volume / total volume) utilized

-PDE's are hyperbolic

-Characteristic wave speeds: $u_1, u_2, u_1 \pm c_1, u_2 \pm c_2$

-Dynamic compaction equation employed for closure

-Number of particles conserved

-Compressible spherical reactive particles

-Simplified drag and convective heat transfer relations

-Virial gas equation of state for inert gas

-Tait equation of state for reactive particles

-Viscosity or **heat conduction in gas not considered**

-Viscosity or **heat conduction in solid not considered**

-Radiation not considered

Two-Phase Model Equations

-ordinary differential equations in steady wave frame

-ξ = distance in steady wave frame $\xi = \xi - Dt$

-D = steady wave speed

-with additional algebraic equations, the model can be represented by four differential equations in four unknowns

$$\frac{d}{d\xi}\left(\rho_2\phi_2 v_2\right) = -\left(\frac{3}{r}\right)\rho_2\phi_2\alpha P_1^m H(T_2 - T_{ig}),$$

particle mass

$$\rho_2\phi_2 v_2\frac{dv_2}{d\xi} + \frac{d}{d\xi}\left[P_2\phi_2\right] = -\beta\frac{\phi_1\phi_2}{r}\left[v_2 - v_1\right],$$

particle momentum

$$\rho_2 v_2\frac{de_2}{d\xi} + P_2\frac{dv_2}{d\xi} = -h\frac{\phi_1}{r^{1/3}}\left[T_2 - T_1\right],$$

particle energy

$$v_2\frac{d\phi_2}{d\xi} = \frac{\phi_1\phi_2}{\mu_c}\left(P_2 - P_1 - \frac{P_{20} - P_{10}}{\phi_{20}}\phi_2\right) - \left(\frac{3}{r}\right)\phi_2\alpha P_1^m H(T_2 - T_{ig}).$$

dynamic pore collapse

Conservation Relations

-obtained by integrating conservative differential equations

-initial conditions specify integration constants

1) Mixture mass, momentum, and energy:

$$\rho_1\phi_1 v_1 + \rho_2\phi_2 v_2 = -D\,\rho_a, \qquad \text{mixture mass}$$

$$\rho_1\phi_1 v_1^2 + P_1\phi_1 + \rho_2\phi_2 v_2^2 + P_2\phi_2 = \rho_a D^2 + P_a, \qquad \text{mixture momentum}$$

$$\rho_1\phi_1 v_1\left[e_1 + v_1^2/2 + P_1/\rho_1\right] + \rho_2\phi_2 v_2\left[e_2 + v_2^2/2 + P_2/\rho_2\right] = -\rho_a D\left[e_a + D^2/2 + P_a/\rho_a\right],$$

mixture energy

- "a" denotes apparent or bulk initial property

$$\rho_a = \rho_{10}\phi_{10} + \rho_{20}\phi_{20}, \qquad \text{apparent initial density}$$

$$P_a = P_{10}\phi_{10} + P_{20}\phi_{20}, \qquad \text{apparent initial pressure}$$

$$e_a = \frac{\rho_{10}\phi_{10}e_{10} + \rho_{20}\phi_{20}e_{20}}{\rho_{10}\phi_{10} + \rho_{20}\phi_{20}}. \qquad \text{apparent initial energy}$$

2) Particle number equation:

$$r = r_0 \sqrt[3]{\frac{-v_2\,\phi_2}{D\,\phi_{20}}}.$$

Gas and Particle State Equations

1) Gas:

$$P_1 = \rho_1 R T_1 \left(1 + b\rho_1\right), \qquad \text{gas thermal}$$

$$e_1 = c_{v1} T_1. \qquad \text{gas caloric}$$

2) Particle:

$$P_2 = \left(\gamma_2 - 1\right) c_{v2} \rho_2 T_2 - \frac{\rho_{20}\sigma}{\gamma_2}, \qquad \text{particle thermal}$$

$$e_2 = c_{v2} T_2 + \frac{\rho_{20}\sigma}{\gamma_2 \rho_2} + q. \qquad \text{particle caloric}$$

Saturation condition:

$$\phi_1 + \phi_2 = 1.$$

Initial Conditions

-Eight independent initial conditions specified for original eight differential equations

-Temperature and density for each phase

-Velocity for each phase

-Initial particle radius

-Initial volume fraction

$$\rho_2 = \rho_{20}, \quad \phi_2 = \phi_{20}, \quad v_2 = -D, \; T_2 = T_0.$$

$$\rho_1 = \rho_{10}, \quad v_1 = -D, \quad T_1 = T_0, \quad r = r_0.$$

-Specified so that initial state is an equilibrium state

-Remaining initial conditions fixed by state equations and saturation condition:

$$P_{10} = \rho_{10} R T_0 \left(1 + b\rho_{10}\right), \quad e_{10} = c_{v1} T_0,$$

$$P_{20} = \left(\gamma_2 - 1\right) c_{v2} \rho_{20} T_0 - \frac{\rho_{20}\sigma}{\gamma_2}, \quad e_{20} = c_{v2} T_0 + \frac{\sigma}{\gamma_2} + q,$$

$$\phi_{10} = 1 - \phi_{20}.$$

Dimensional Input Parameters

a	[m / (s Pa)]	2.90×10^{-9}
ρ_{10}	[kg / m^3]	1.00×10^{0}
m		1.00×10^{0}
β	[kg / (s m^2)]	1.00×10^{4}
ρ_{20}	[kg / m^3]	1.90×10^{3}
h	[J / (s K m$^{8/3}$)]	1.00×10^{7}
c_{v1}	[J / (kg K)]	2.40×10^{3}
c_{v2}	[J / (kg K)]	1.50×10^{3}
R	[J / (kg K)]	8.50×10^{2}
σ	[(m / s)^2]	7.20×10^{6}
q	[J / kg]	5.84×10^{6}
r_0	[m]	1.00×10^{-4}
b	[m^3 / kg]	1.10×10^{-3}
γ_2		5.00×10^{0}
μ_c	[kg / (m s)]	1.25×10^{2}
T_0	[K]	3.00×10^{2}
T_{ig}	[K]	$3.00 \times 10^{2+}$

Two-Phase Deflagration End States

-arbitrarily assume complete reaction

-mixture equations define two-phase Rayleigh line and Hugoniot equations

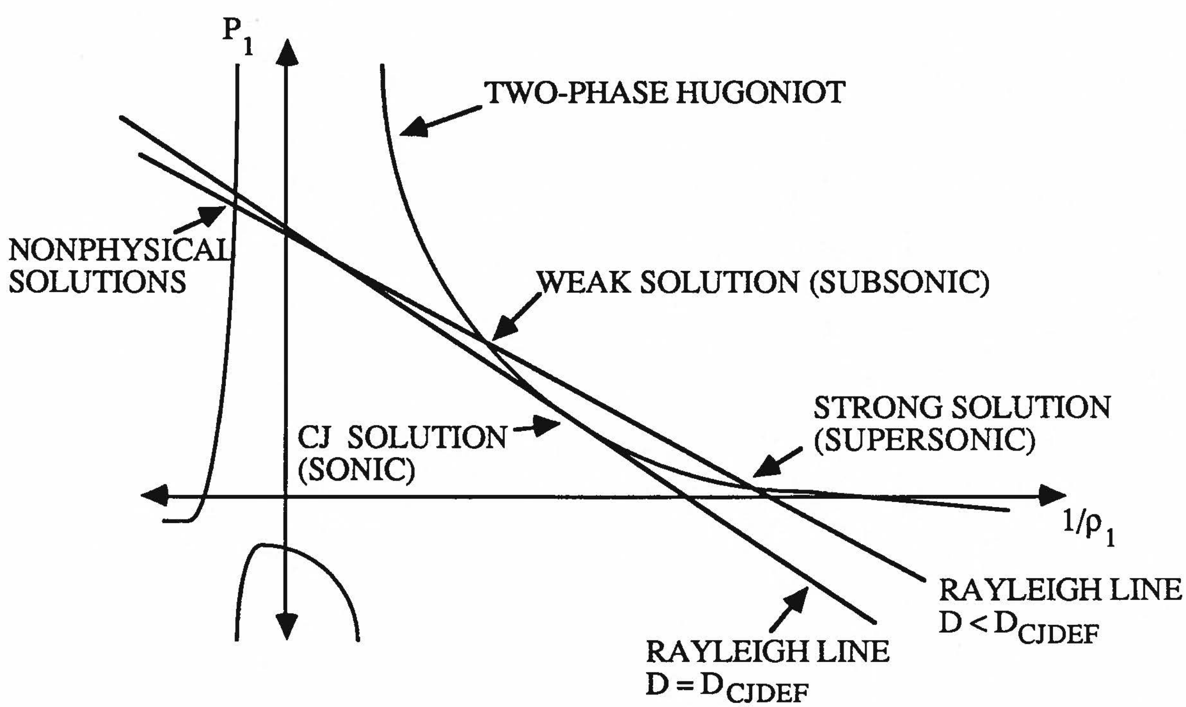
$$P_1 = P_a + \rho_a^2 D^2 \left(1/\rho_a - 1/\rho_1 \right), \qquad \text{Rayleigh line}$$

$$\frac{(P_a + P_1)(1/\rho_1 - 1/\rho_a)}{2} + \frac{c_{v1} P_1}{R\rho_1 (b\rho_1 + 1)} - e_a = 0. \qquad \text{Hugoniot}$$

-In general, two physical deflagration solutions for a given wave speed D

1) Low pressure, supersonic, strong solution
2) High pressure, weak, subsonic solution

-Maximum deflagration wave speed at CJ condition, sonic solution

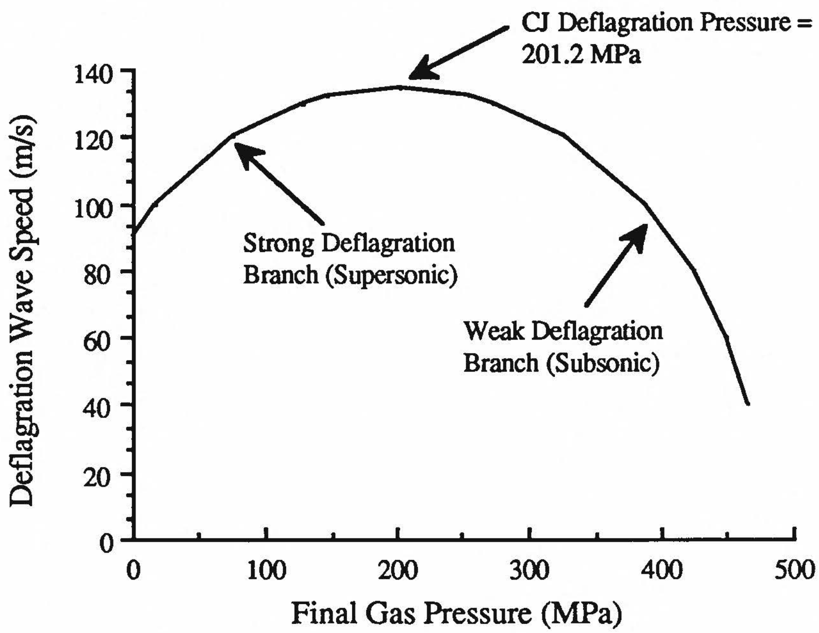


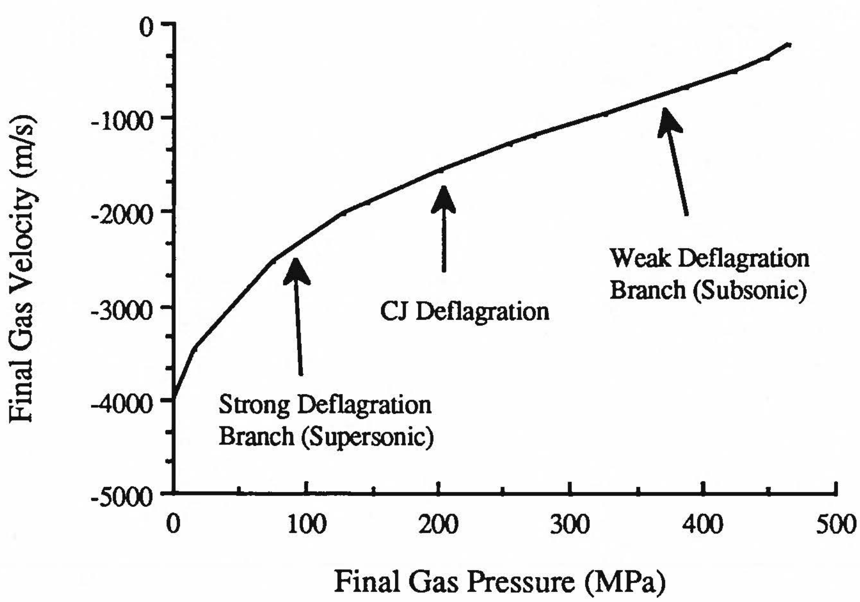
Complete Reaction End State

-assume exhaust pressure can be controlled

-deflagration wave speed and all gas phase properties then known as functions of exhaust pressure

-ϕ_{20} = 0.70





CJ Deflagration State

-CJ state can be determined numerically

-Simple analytic expression in two limits

1) ideal gas $b = 0$
2) $P_a/(\rho_a e_a) \rightarrow 0$

$$D_{CJ} \cong \sqrt{\frac{\gamma_1^2 e_a}{2(\gamma_1^2 - 1)}\left(\frac{P_a}{\rho_a e_a}\right)},$$

$$P_{CJ} \cong \frac{1}{\gamma_1 + 1} P_a,$$

$$\rho_{CJ} \cong \frac{\gamma_1}{2(\gamma_1 - 1)}\left(\frac{P_a}{\rho_a e_a}\right) \rho_a,$$

$$T_{CJ} \cong \frac{2}{\gamma_1 (\gamma_1 + 1)} \frac{e_a}{c_{v1}},$$

$$e_{CJ} \cong \frac{2}{\gamma_1(\gamma_1 + 1)} e_a,$$

$$v_{CJ} \cong u_{CJ} \cong - \sqrt{\left(\frac{2(\gamma_1 - 1)}{\gamma_1 + 1} e_a\right)} .$$

Two-Phase Deflagration Structure

-Ordinary differential equations integrated for D = 100 m/s

-Arbitrarily assumed that no shocks exist in structure or no sonic points

-With this assumption the end state is weak subsonic end state

-exhaust pressure ~ 400 MPa

-Extreme deflagration exhaust conditions because some parameters arbitrarily chosen so that a numerically resolved structure could be presented

-No two-phase steady deflagration structure going to complete reaction was found

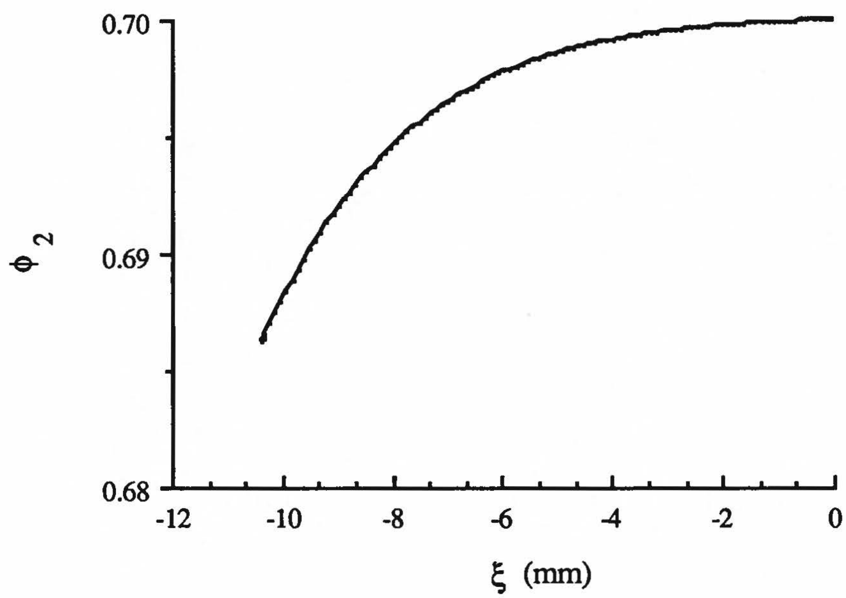


Figure 7 Solid Volume Fraction Structure, $\phi_{20} = 0.70$, D = 100 m/s

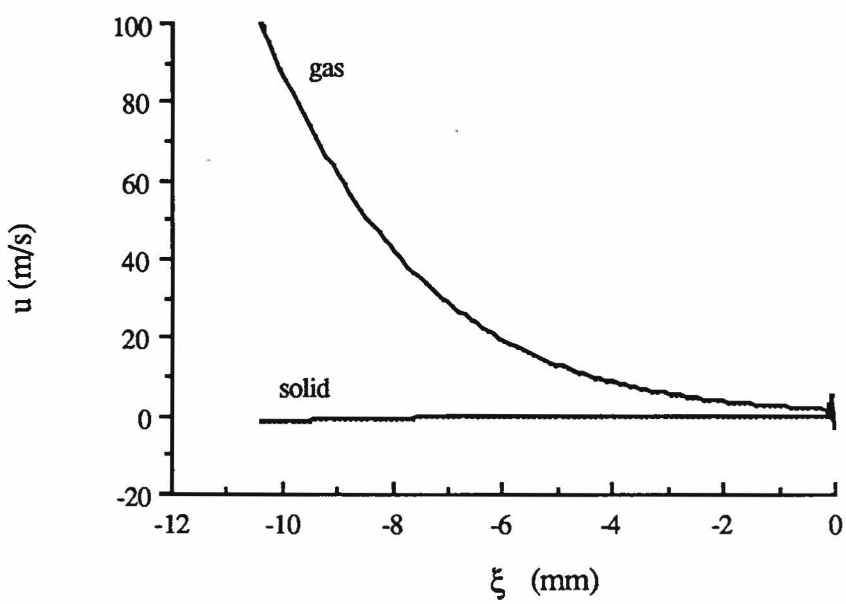


Figure 8 Gas and Solid Lab Velocity Structure, $\phi_{20} = 0.70$, D = 100 m/s

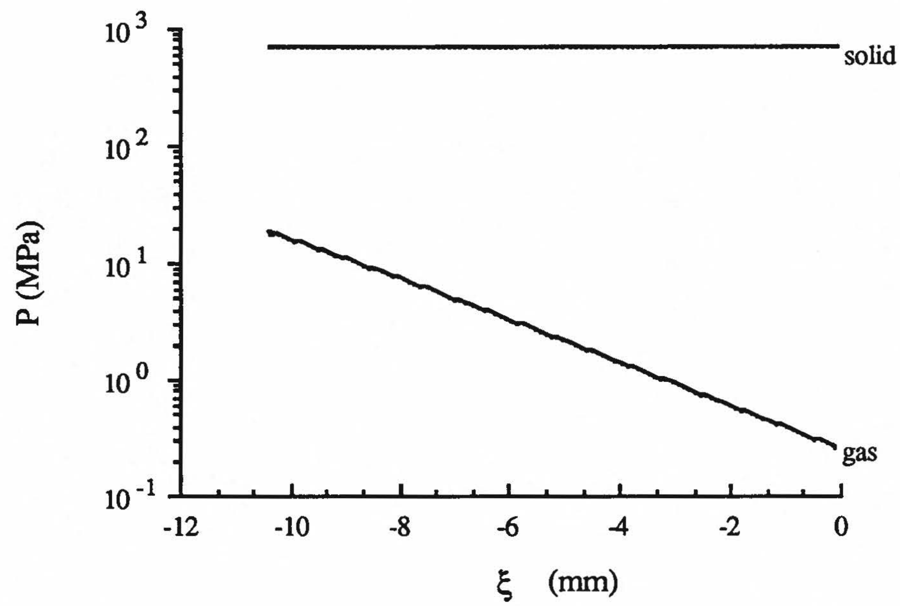


Figure 9 Gas and Solid Pressure Structure, $\phi_{20} = 0.70$, D = 100 m/s

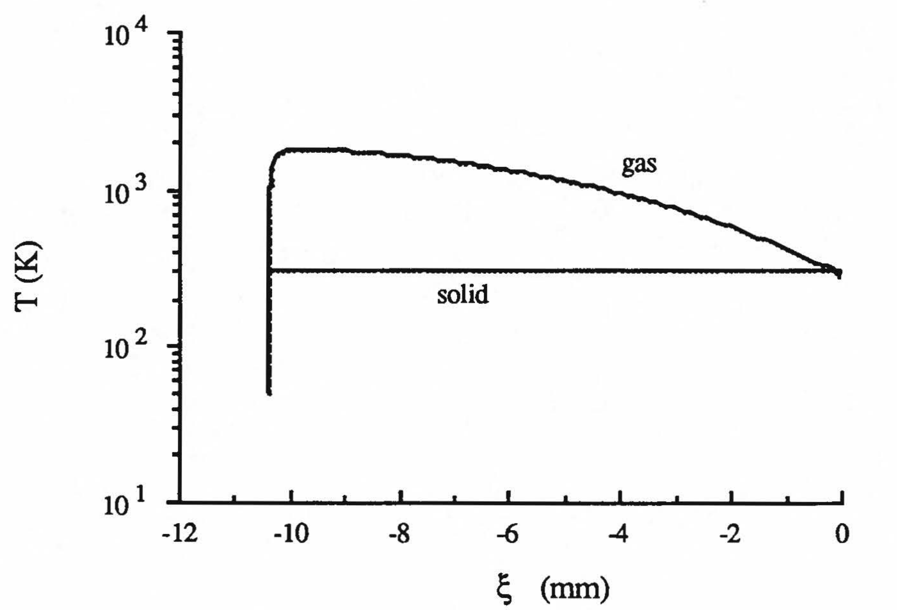


Figure 10 Gas and Solid Temperature Structure, $\phi_{20} = 0.70$, D = 100 m/s

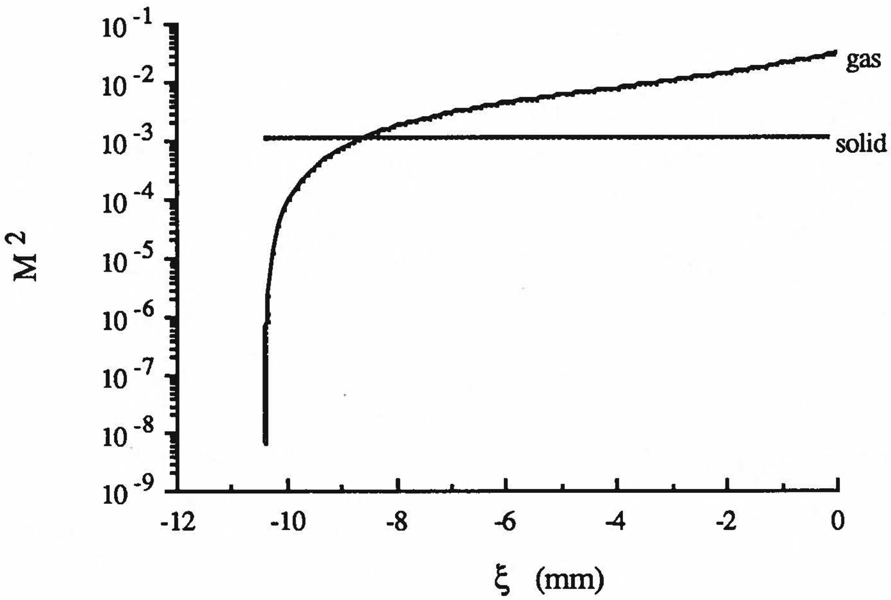


Figure 11 Gas and Solid Mach Number Squared, $\phi_{20} = 0.70$, D = 100 m/s

Conclusions

-Possible to predict gas phase deflagration end state and wave speed as function of exhaust pressure and initial conditions

-For the region of parameter space studied, no steady two-phase deflagration structure exists

-Processes that support detonation are not sufficient to support a two-phase deflagration

-It may be necessary to include heat conduction and radiation to model two-phase deflagrations

-Combustion of granulated propellants could possible accelerate into steady, self-propagating two-phase detonation