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MODELED HEATING AND SURFACE EROSION COMPARING MOTILE (GAS BORNE) AND STATIONARY (SURFACE COATING) INERT-PARTICLE ADDITIVES*

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ABSTRACT

The unsteady, non-similar, chemically reactive, turbulent boundary layer equations are modified for gas plus dispersed solid particle mixtures, for gas phase turbulent combustion reactions and for heterogeneous gas-solid surface erosive reactions. The exterior (ballistic core) edge boundary conditions for the solutions are modified to include dispersed particle influences on core propellant combustion-generated turbulence levels, combustion reactants and products, and reaction-induced, non-isentropic mixture states. The wall surface (in this study it is always steel) is considered either bare or coated with a fixed particle coating which is conceptually non-reactive, insulative, and non-ablative. Two families of solutions are compared. These correspond to: (1) consideration of gas-borne, free-slip, almost spontaneously mobile (motile) solid particle additives which influence the turbulent heat transfer at the uncoated steel surface and, in contrast, (2) consideration of particle-free, gas phase turbulent heat transfer to the insulated surface coated by stationary particles. Significant differences in erosive heat transfer are found in comparing the two families of solutions over a substantial range of interior ballistic flow conditions. The most effective influences on reducing erosive heat transfer appear to favor mobile, gas-borne particle additives.

INTRODUCTION

In a recent publication[1] we summarized the findings of our research over the last four years on fundamental mechanisms of erosion. One of the questions emphasized in our studies of erosive environments is the identification and evaluation of the influence of erosion reducing additives. We want to understand if they work, how they work and how effective they are. Many of the questions about the use of additives for erosion reduction such as their active or catalytic influence on gas phase reactions or their influence on the gas-to-solid surface reactions with thermal radiation remain. These questions form a major part of our present or future experimental and theoretical investigations. Here, however, it is useful to apply some theoretical tests to the issue of whether inert solid particle additives are more effective if introduced as gas-borne and free to disperse or if fixed to the wall as an insulative coating.

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Either introducing additives as a freely dispersed phase or applying them as a semi-stationary liner or coating at the metal surface appear to be effective in reducing erosion. Experiments and firing tests seem to support the view that at least some types of additives significantly reduce erosion and extend the useful life of the working container surface (whether it is a cylindrical barrel or a contoured convergent divergent rocket propellant nozzle). However quantitative consistency and definitive information on the sensitivity of the additive influence with respect to size, material composition and state, concentration, placement and the manner in which the additives are introduced seem to be lacking. A goal of our current and on-going investigations is to shed some light on these questions and to provide some quantitative results in evaluating their influence on solid propellant combustion, flow, and erosion processes.

In-situ firing tests and laboratory based combustion generated erosion simulators provide the majority of the data available for erosion analysis. However, unfolding the influence of any single mechanism and, indeed, even the evaluation and analysis of the data for consistency and trends is difficult, if not impossible. Some simplification of the experimental configuration and implementation of prescribed, specific controls on the experimental conditions and process evolution throughout its test duration is needed. Appreciation of some of the interpretation difficulties may be derived from reading descriptions of the substantial recent efforts of Army scientists.[2,3] These efforts aim at evaluating the heat transfer to gun tubes and attempting to interrelate the different conditions based on (integrated over time) heat load or heat input. Direct effects of material micro-structural response and resultant characterization are intangibly lost, since the integral of the heat flux is a non-unique characterization of the heat transfer environment. Addition of a change in test configuration[4,5] only adds to the difficulty of relating the heat transfer information to erosion to any real system, in the absence of information on all scale factors (including time) which may control the evolution of the process.

It is apparently difficult to unfold the sensitivity of the unsteady influences, and account for configuration effects and scale effects even in a systematic data scatter and error analysis.[6] Evaluating more subtle influences such as one anticipates with additives as to their size, composition, and concentration influences is, we judge, even more difficult.

In view of this we adopt a different approach. We attempt to decompose the more complicated physical system into a set of simpler, more controllable, experiments. We further develop our investigations by devising and conducting both the experimental and theoretical investigations coincidentally and in parallel.[7,8,9] In our view it is encouraging to observe the development of similar joint theoretical and experimental efforts through Army collaboration with West German scientists over the past two years.[10,11] These efforts together with the basic shock tube research in Great Britain on reduction of turbulent wall heat transfer in particle laden flows represent a potentially major new source of appropriately controlled fundamental and useful information on the mass laden turbulent erosive heat transfer process.[17]

The questions that appear, theoretical considerations and experimental observations necessitate forming a global view (from wall to wall) of the combustion

chamber. We analyze the combustion process from its instigation until a substantial portion of the combustion generated impulse wave has decayed (usually an e-fold decay, relative to the maximum pressure pulse). Necessarily, however, systematic study of the erosion process requires that our final attention must be placed on a very much smaller portion of the global flow field. This is the wall boundary layer region consisting of the steepest flux gradients and the corresponding maximum erosion activity.[13,14,15]

PROCEDURE AND DISCUSSION

In the interest of spatial compactness in this article we will avoid extensive mathematical development and limit our illustrations to a minimum of figures necessary to support the discussion. We will cite, wherever necessary, the several open literature references in which more of the detail, omitted here, is available.

Perhaps the two most revealing factors pertinent to the stage of our investigation discussed here are first, the presence of a continuous distribution of turbulence energy (from combustion generated free core turbulence to wall generated boundary layer turbulence) and second, the existence of a threshold of inert particle size (about 1 micron) below which particles act to reduce erosion and above which particles act, in general, to enhance it.

In our study we preserve the continuity of turbulence from core to wall throughout the chamber by using two overlapping (asymptotically matched) solution procedures. One is a generally three-dimensional Navier-Stokes plus Lagrangian particle field solution procedure.[7,8,9] This extends, conceptually from the bounding chamber (or tube) walls throughout the combustion core in the mixed phase flow field region which grows between the relatively slowly expanding propellant bed and the more rapidly moving projectile it accelerates. The second solution procedure magnifies the all-important boundary layer region for further detailed study. It is computationally efficient to match the unsteady, chemically reactive multi-component turbulent boundary layer solutions at selected small intervals of time to the core solutions. The chosen intervals are those which we judge to be critical phases in the combustion flow evolution, boundary layer structure evolution and corresponding changes to heat, mass and momentum (wall shear stress) transport.[13,14,15]

Figure 1 illustrates the experimentally observed continuous distribution of turbulence intensity which extends from a combustion generated mixing region (in this case a combustion mixing free shear layer emanating from the splitter plate dividing a two channel rectangular combustion tube) to the chamber walls. The turbulence intensity is defined as the localized (space and time resolved) root mean square of the statistical velocity fluctuations ratioed to the local mean flow velocity. The distribution of values in mean flow velocity are shown in the upper frames at several designated streamwise locations, measured downstream of the splitter plate trailing edge. The lower frames illustrate values of the turbulence intensity measured with non-intrusive laser Doppler anemometer (LDA) techniques in our University of California, Berkeley combustion test facility.[8,9] The two channel rectangular combustion tube facility is a propane combustion flow tube with provision for a variation in flow speeds from about 10 to 20 m/s, for variation of air-fuel mixture ratios at the splitter plate, and for introduction

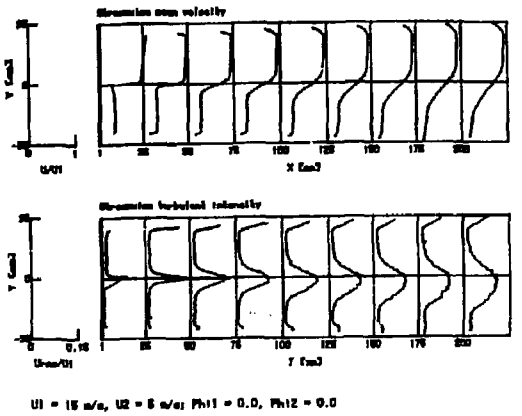

Fig. 1 LDA traces of mean two channel velocity profiles (above) and turbulent intensities (below) at listed stations.

of a range of concentrations of arbitrarily sized inert solid particles in the free shear layer. The experimental configuration is shown in Fig. 2.

The basic ingredients of the particle field plus time evolving but mean averaged (with respect to high frequency fluctuating velocity components) computational model include three interactive phases. One phase is an axially symmetric or plane two dimensional finite difference procedure for numerical integration of the time dependent Reynolds and Favre' averaged compressible Navier-Stokes equations. This also includes a volumetric node-to-node averaging for particle plus gas mixtures, and provision for finite rate kinetics with up to twenty matrix reaction equations.

The second computational phase includes both two- and three-dimensional time-dependent Lagrangian center-of-mass particle trajectory, momenta, and energy expectancy computations. The third phase is, conceptually, a statistical overlap between the other two fields. This third phase is basically a Monte-Carlo stochastic mixing phase which randomly samples the turbulent velocity expectancies and applies these in discrete time steps to the particle field through a set of self-consistent, velocity fluctuation dependent, particle-gas and particle-particle force laws.[7,8,9]

Using this procedure we compute turbulent intensity distributions in the rectangular geometry and under the experimental conditions previously described with respect to Fig. 1. The computed, predicted distributions, shown in Fig. 3, display, qualitatively, the same continuous profiles of intensity as those shown experimentally for the corresponding combustion test case in Fig. 1. Here, in Fig. 3, we also predict the influence of small particle mass loading, $K_m = 0$ (no particles) and $K_m = 0.002$ (about 1.3×10^4 cm^{-3} of 0.5 micron Ti_2O particles). The mass loading parameter, K_m, is defined as the ratio of the mass of the particles in a unit volume to the sum of the mass of the gas and particles in the same volume. We see that even for very modest particle concentrations, the level of

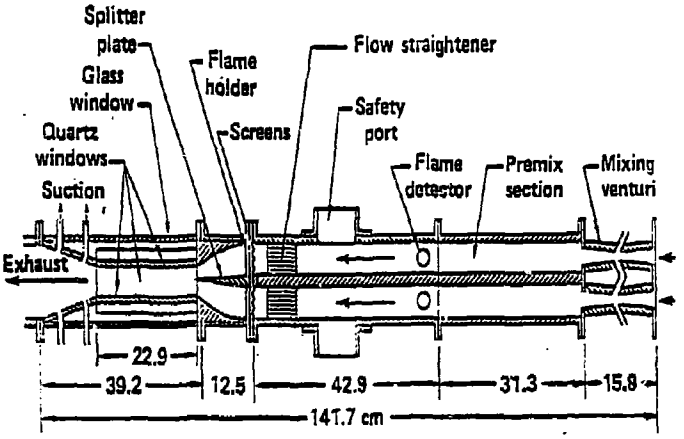

Fig. 2 Turbulent combustion free shear layer mixing two channel combustion tube for vapor phase and particle laden experiments. Dimensions shown are in cm.

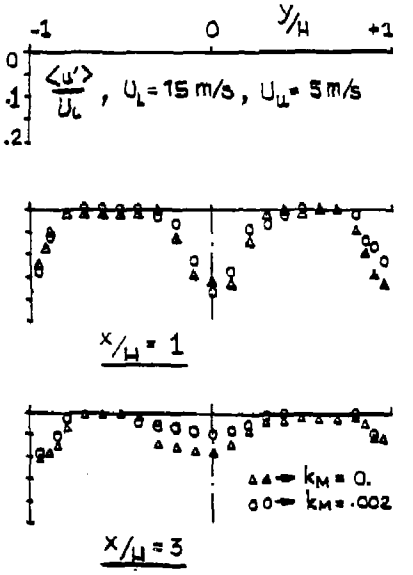

Fig. 3 Computer predictions of two-channel turbulent intensity profiles at listed stations, for the experimental flow conditions in Fig. 1. Particles are 0.5 μm diameter.

turbulence as measured by its local turbulence intensity is predicted to be significantly reduced. This is the potential, dominant, inertial mechanism for reduction of turbulent mixing, transport and consequent reduction of erosive heat, mass and momentum transfer. It results from addition of small (submicron) particles which relax almost instantaneously to the local mean gas field velocity.

Next we investigate a theoretically magnified view of the wall boundary layer region and alterations to its structure when even minute concentrations, $\mathcal{O}(10^5\ cm^{-3})$, of small inert particles are entrained. In order to simulate boundary layer structure changes in the presence of such particle mass loadings we asymptotically match the turbulent, finite-rate reactive, multi-component mixed phase boundary layer solution procedure to the previously described global mixture phase and particle field computations. The asymptotic matching procedure and results of parametric tests with boundary layer structure and altered flow conditions have been developed and described in previous articles.[13,14] Here, we summarize.

Let $K(\vec{r},t)$ and $\varepsilon(\vec{r},t)$ be the space and time distributions of turbulence kinetic energy and turbulence dissipation rate, respectively. The transformed turbulent boundary layer stream function is represented by f, so that the parallel velocity is given by f' and its gradient with respect to the normal-to-the-wall distance is given by f", where primes denote differentiation with respect to this normal distance. The asymptotic outer edge position for the matching is then designated with the symbol ∞.

The conventional boundary layer matching conditions for a reacting ($\partial C_J/\partial t \neq 0$) where C_J is a species component), non-isentropic ($\partial s/\partial t + f' \partial s/\partial x \neq 0$) mixed conditions are expressed as,

$$\frac{\partial C_J}{\partial t} = \frac{\partial C_J}{\partial t}\,(\infty),\ \frac{\partial s}{\partial t} + f' \frac{\partial s}{\partial x} = \frac{\partial s}{\partial t}\,(\infty),\ K(\infty),\ \varepsilon(\infty),\ f''(\infty) = 0. \qquad (1)$$

For the modified overlap region in our matching procedure they are identical to eq. (1) except that the vanishing turbulence kinetic energy and dissipation are replaced by local *minima constraints*,

$$K'(\infty),\ \varepsilon'(\infty) = 0\ . \qquad (2)$$

The molecular gas transport coefficients are computed locally in the mixture boundary layer once the local particle dispersal and mass loading distribution is determined,

$$K_p(x, y, t) = K_m(x, y, t) + 1\ .$$

The space, time distributions of viscosity, conductivity and self diffusion, μ, K_T, D_J are then computed from an elementary application of Enskog theory which results in a first approximation for the two phase mixture for light particle loading (neglecting *instantaneous* changes to intermolecular cross sections and collision frequencies),

$\mu = \mu^0/\kappa_p$, D_J^0/κ_p and κ_T from the renormalized Prandtl No., N_{PR}, (3)

$$N_{PR} = \left(\frac{\mu c_p}{\kappa_T}\right)^0 \cdot \left[\frac{1 + \kappa_m c_s^0/c_p^0}{\kappa_p}\right].$$

In the foregoing relations, superscript (0) refers to the locally computed pure gas thermal or transport properties while c_s and c_p are the solid particle heat capacity and gaseous specific heat respectively.

To compare our gas borne additive effectiveness with a fixed particle-in-binder coating layer as an insulative wall coating such as examined by Russell,[16] we make the following initial assumptions. First, the coating of particle-plus-binder (phenolic or glue) possesses a very low equivalent thermal conductivity (say equal to a graphite layer) and is uniformly applied and remains throughout at a depth of 5 mm as a coating around a cylindrical barrel-like container. We consider a streamwise wall segment 1 cm long, axially. An equivalent number density of uniformly distributed 0.5 micron particles in the central core of a 15.5 cm diameter cylinder (neglecting convection velocity distribution) is found to be about 6×10^{10} cm^{-3}. With a conservative estimate of the convective entrainment (ignoring boundary layer capture and particle concentration buildup) we estimate that a minimum of 6×10^5 cm^{-3} uniformly distributed particles populate the boundary layer wall region. Actually, using more detailed entrainment and statistical average dispersion calculations we have estimated that the boundary layer mixture may yield concentrations of particles about two orders of magnitude higher than those used here for our comparisons.[13,14] However, even applying these seemingly pessimistic concentration estimates to our analysis we predict the encouraging results shown in Fig. 4. Here the open circles represent a range of (peak) heat flux values delivered to the bare surface, while the filled circles and filled squares represent the modulated heat flux actually sensed through (i) the fixed coating layer and (ii) the gas-borne additive distribution, respectively. Either of the particle additive situations: the optimistically *invariant, non-degrading liners, or the pessimistically sparse gas borne particles* yield about the same level of reduction in heat transfer flux delivered at the wall surface. These heat flux data are plotted against the Reynolds' No., R_e^*, based on the chamber diameter, the mean flow density, and mean velocity at the peak of the gas phase heat pulse.

While direct measurement of the particle laden wall boundary layer shear and heat transfer are not yet available from our University of California, Berkeley experiments, the collaborative University of Southampton dusty gas shock wave driven turbulent boundary layer measurements (to date)[12] have indicated convincingly similar reductions in wall heating with particle entrainment (15%-30%).

SUMMARY

It appears that within the next few years we will have a useful understanding about particle additives and particle residue interaction in solid propellant

combustion erosion. Experimental verification and guidance is beginning to accumulate. The importance of this topic in erosion studies is evident on reflecting that the gas borne particles significantly influence not only the erosion but also the basic propellant combustion process itself by viscous and eddy damping, catalytic or reactive interaction with the kinetics, and scattering and absorption in the closely related thermal radiation transport processes. It is also encouraging to view the interest and emphasis placed on this area of research by our European colleagues in active collaboration with the Army efforts.

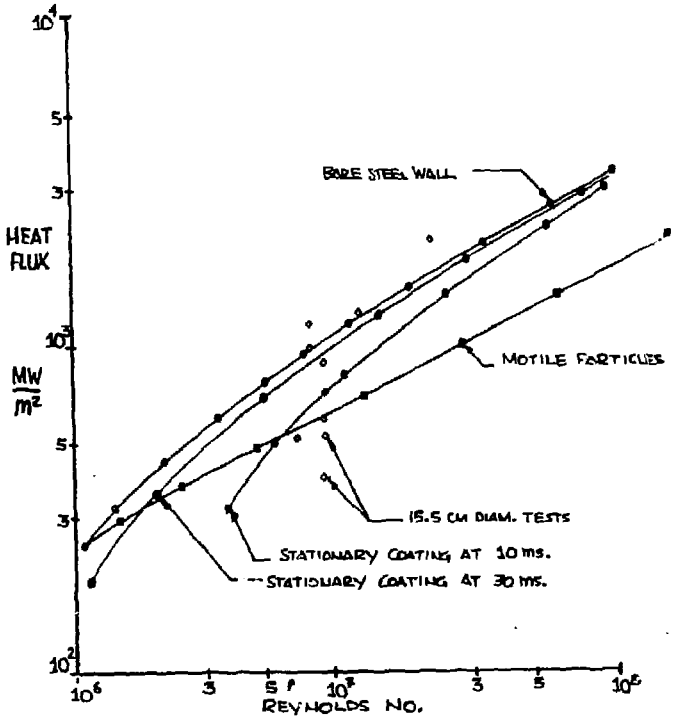

Fig. 4 Heating sensed at a steel surface: (1) directly exposed (2) coated semi-permanently with a 5 mm particle-plus-binder layer and (3) dispersed gas borne inert, non-reactive particles.

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