DETAILED STUDIES ON FLAME EXTINCTION BY INERT PARTICLES IN NORMAL- AND MICRO-GRAVITY

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INTRODUCTION

The combustion of dusty flows has been studied to lesser extent than pure gas phase flows and sprays. Particles can have a strong effect by modifying the dynamic response and detailed structure of flames through the dynamic, thermal, and chemical couplings between the two phases. A rigorous understanding of the dynamics and structure of two-phase flows can be attained in stagnation flow configurations, which have been used by others to study spray combustion [e.g. 1-3] as well as reacting dusty flows [e.g. 4, 5].

In earlier studies on reacting dusty flows [e.g.4, 5], the thermal coupling between the two phases as well as the effect of gravity on the flame response were not considered. However, in Ref. 6, the thermal coupling between chemically inert particles and the gas was addressed in premixed flames. The effects of gravity was also studied showing that it can substantially affect the profiles of the particle velocity, number density, mass flux, and temperature. The results showed a strong dynamic and thermal dependence of reacting dusty flows to particle number density. However, the work was only numerical and limited to twin-flames, stagnation, premixed flames.

In Ref. 7 the effects of chemically inert particle clouds on the extinction of strained premixed and non-premixed flames were studied both experimentally and numerically at 1-g. It was shown and explained that large particles can cause more effective flame cooling compared to smaller particles. The effects of flame configuration and particle injection orientation were also addressed. The complexity of the coupling between the various parameters in such flows was demonstrated and it was shown that it was impossible to obtain a simple and still meaningful scaling that captured all the pertinent physics.

OBJECTIVES

The objective of the present work was to conduct a combined experimental and numerical study to assess the effects of chemically inert particles on flame extinction in 1-g and μ-g environments. Numerical simulations were compared with experimental results to verify the validity of theoretical models. The results were used to derive physical insight into the mechanisms that control the dynamic and thermal interactions between the two phases.

EXPERIMENTAL APPROACH

The experimental configuration includes the use of two counterflowing jets. Particles are fed into the flow by using a particle seeder unit, which utilizes a piston feeder similar to that used in [8]. This feeder is attached beneath the bottom burner and feeds the particles into the flow at a constant rate. This design allows for seeding under both 1-g and μ-g. However, it is apparent that the particle pickup is strongly affected by gravitational forces so that the seeder had to be calibrated separately in 1-g and μ-g. Chemically inert aluminum oxide and nickel-alloy particles were used. (While nickel burns, these fuel-lean flames are too cool to cause nickel ignition).

Premixed and non-premixed flame extinction experiments were conducted, by varying the particle type, size, and mass delivery rate, as well as the gas phase equivalence ratio, fuel type, flame configuration, and strain rate. In all these experiments, the particles were seeded from the lower burner. The experiments in μ-g were conducted on board the KC-135 plane.

Two types of premixed flame configurations were studied. The first included the use of the symmetric twin-flame that results by impinging on each other two fuel/air jets of identical composition. In this configuration, two flames form and the particles, which are injected only through the lower burner, preferentially cool the first flame that they encounter and may or may not have a chance to directly cool the second flame. That depends both on the ability of the particles to penetrate the gas phase stagnation plane (GSP) and on the particle's thermal state as they reach the second flame. The second configuration used is a single flame that results by impinging a fuel/air jet on an opposing air jet. In the non-premixed flame experiments, the mixture of fuel and nitrogen gas was supplied from the bottom burner, while the air jet was supplied from the upper burner.

For all cases, the flames are first established at conditions close to the extinction state. Then, the local strain rate, based on the maximum velocity gradient in the hydrodynamic zone, is measured by using Laser Doppler Velocimetry at 1-g, and is globally determined at μ-g. Subsequently, the piston seeder is turned on, feeding the particles at a constant rate. The fuel flow rate is then decreased very slowly, until the flames are extinguished.

NUMERICAL APPROACH

A set of quasi-one-dimensional equations along the system centerline has been developed for both phases [6]. The particle equations were formulated for small particle number densities. The gas phase continuity and species equations for the inert particles are identical to those of Ref. 9. However, the gas phase momentum equation was modified by adding a term representing the Stokes drag and thermophoretic forces exerted between the particles and the gas, as well as the gravitational force on the particles. (The system configuration is assumed to be vertical so that gravity acts in the axial direction.) Including terms describing the conductive/convective/radiative heat exchange between the two phases also modified the gas phase energy equation. The particle energy equation includes the contributions of conductive/convective heat exchange between the two phases. A conservation equation was also formulated for the particle number density.

The solutions are obtained by simultaneously integrating the entire system of equations for both phases. An Eulerian frame of reference is used for the integration of the gas phase equations. The particle equations are integrated in a Lagrangian frame of reference in order to describe properly the particle reversal phenomenon [1,6]. Detailed kinetics are used, and the code is integrated with the CHEMKIN [10] and Transport [11] subroutine libraries.

SUMMARY OF RESEARCH

It was previously shown experimentally and explained numerically [7] that at low strain rates the cooling efficiency of large particles may be greater compared to that of small particles for the same amount of particle mass delivered into the flow. This counterintuitive finding results from the fact that while similar masses of small particles possess more total surface area, the large particles can establish large temperature differences with the gas phase within the reaction zone, and thus more effectively cool the flame. However, the numerical simulations shown in Fig.1 indicate that as the strain rate increases, the smaller particles cool more effectively. This is also supported by the experimental results for methane/air premixed flames shown in Fig. 2. At high strain rates large particles are quickly transported through the flame and do not remove much heat compared to smaller particles, which more closely follow the flow as they are slowed near the stagnation plane and have a larger residence time in the main reaction zone.

Flame extinction experiments were conducted for twin flames performed in 1-g and μ-g. The experimental data of Fig. 3 indicate that with the same particle mass delivery rate and the same stain rate values (i.e. the same nozzle exit velocity), the particles extinguish stronger flames in μ-g compared to 1-g. This is because at μ-g the particles penetrate all the way to the top flame and thus can affect both flames directly. In 1-g, however, gravity opposes the particle motion so that they can barely cross the GSP and as a result, only the lower flame is cooled. Figure 5 depicts the results of flame extinction experiments conducted by 25- and 60-μm aluminum-oxide particles. It can be seen that the large particles cool the flames to extinction more effectively as they remove more heat from the bottom flame due to their larger thermal inertia and they also affect the top flame directly due to their larger dynamic inertia.

Figure 6 depicts comparisons of experimental and predicted extinction conditions for single premixed methane/air flames stabilized below GSP and seeded with 37-μm nickel-alloy particles in 1-g. It is apparent that a good agreement exists, considering that various assumptions are involved in both experiments and simulations. However, the simulations systematically predict larger particle mass delivery rates for a particular extinction equivalence ratio. This may result from the fact that the code is quasi-one dimensional while the actual flow field is axisymmetric. In other words the code only defines properly the dynamic and thermal behavior of the particles along the stagnation streamline, which may be different from the behavior of the particles that are not at the vicinity of the centerline.

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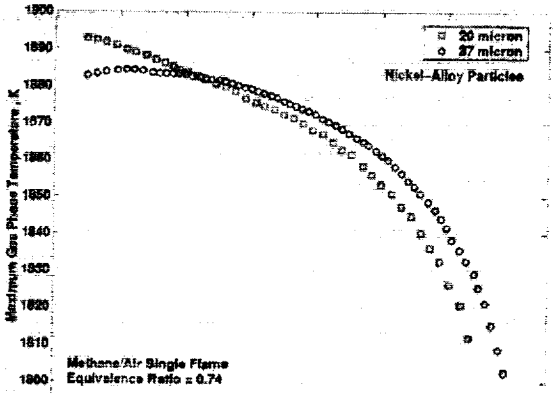


Figure 1

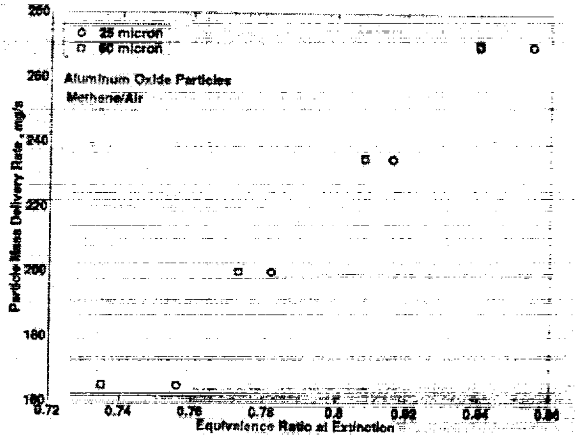


Figure 2

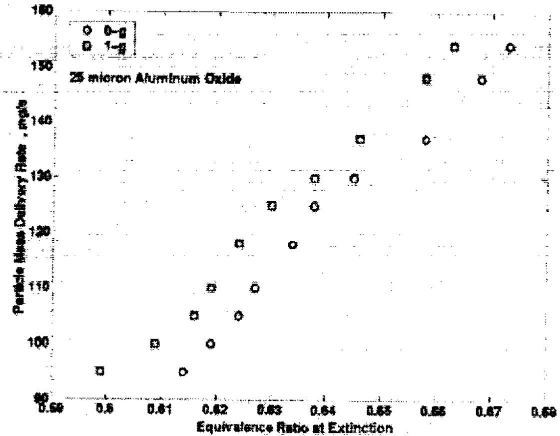
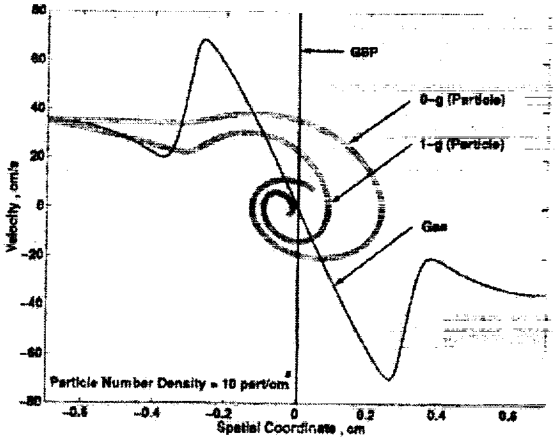


Figure 3



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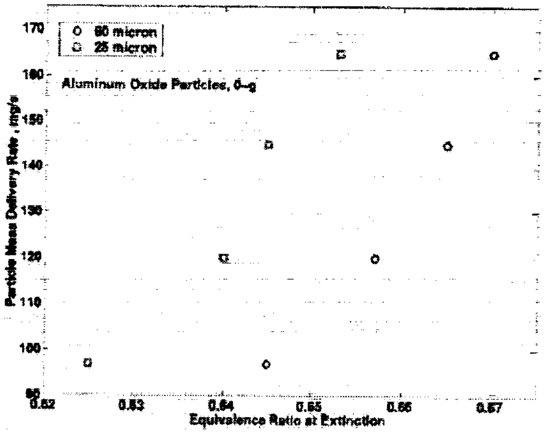

Figure 5

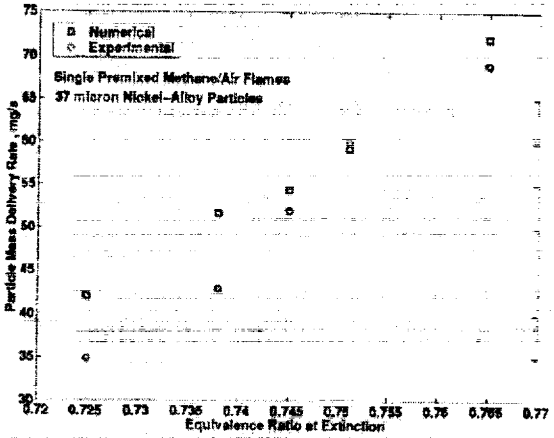

Figure 6