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Perforated Porous Plate Burner to Model Composite Propellant Combustion

Kumar Ramohalli* and Kiran Magiawala†
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif.

Abstract

THE concept of a perforated porous plate burner is presented. The burner scale models the principal details of the vapor phase in nonmetallized composite propellants. Vapor evolution from the continuous binder is simulated by gaseous fuel transpiration through a woven porous plate; discrete vapor evolution from the oxidizer particles is simulated by gaseous oxidizer passage through perforations in the porous plate. The 1.2 mm-diam perforations establish the flame at a distance of the order of millimeters above the surface according to dimensional analysis and mixing controlled combustion assumption.[1] The flame standoff distance is measured with variations in the flow rate of reactants, mean pressure, and oscillations of reactant feed rates. By isolating the condensed phase and surface details present in propellants, the expanded vapor phase lends itself to easy analysis. Interpretation in terms of a one-dimensional theory yields the surface heat transfer rate as a function of measured variables. Direct visualizations of the flame structure vividly reveal several details in heterogeneous combustion.

Contents

The concept of scale modeling the vapor-phase combustion in heterogeneous propellants is developed. Based on the assumption of mixing controlled combustion, scaling rules suggest[1] that the flame standoff distance should scale with the heterogeneity of oxidizer vapor evolution, namely the particle size.

Discrete perforations in a porous plate simulate the heterogeneity. The continuous binder phase is simulated with fuel vapor evolution through the porous plate. This design is believed to be an improvement over the cluster tube designs of Van Tiggelen[2,3] and Hermance and Ramlal[4] in that: 1) the binder vapor evolution is better modeled through the continuous porous plate matrix; 2) the surface temperature can be measured; 3) an important aspect of propellant combustion, i.e., pressure dependence, has been studied; 4) the oscillatory behavior of the vapor phase flame zone is also studied. As Van Tiggelen and co-workers recognize, there exist practically unlimited variations in the experiments that can simulate propellant combustion. Premixing the oxidizer with a fuel models the monopropellant oxidizer flame. Premixing the fuel with an oxidizer models energetic binders. Various chemical species can be mixed with either (or both) of the gas streams to model the effects of minor additives on vapor phase combustion.

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*Group Supervisor. Associate Fellow AIAA.
†Research Fellow in Jet Propulsion. Member AIAA.

The flame standoff distance is the primary experimental output, while the reactant flow rates, mean chamber pressure, and frequency of flow oscillations are input variables. A simple theory relates the flame standoff distance to the surface heat transfer rates.

Analysis

The one-dimensional, thin flame assumption is used. The vapors leaving the propellant surface do not combust until they reach a distance X^* from the surface; they combust completely in a thin zone (of thickness $\ll X^*$) at X^*. The flame temperature T_b is reached at X^*. The solution to the heat transfer equation $k(d^2T/dx^2)+\rho cu(dT/dx)=0$ with $X=0$; $T=T_s$ and $X=X^*$; $T=T_b$ yields

$$q_s''=k(dT/dx)_s=\rho uc(T_b-T_s)/[1-\exp(\rho cux^*/k)]$$

where k is the thermal conductivity coefficient for the vapors, T the temperature, X the distance normal to the surface, ρ the vapor density, c the specific heat, u the flow velocity, and q_s'' the heat transfer rate to the surface at surface temperature T_s. T_b is determined by a choice of the reactants, u is set by the experiment, ρ is determined by the operating pressure. Thus, the measured X^* dependence on u and pressure also sheds light on the influences of fluid dynamics and chemical kinetics in vapor phase combustion.

Experimental Research

The burner is shown in Fig. 1. It consists of 2.54-mm-thick woven stainless steel porous plate of 12.7-μm equivalent porosity, through which the fuel gas is injected. The oxidizer gas evolution from particles is simulated by 120 tubes passing through the porous plate. The overall diameter is 5 cm. The tube internal diameter of 1197 μm was chosen to avoid turbulence at larger diameters (due to the classical transition in pipe flow at a Reynolds number of 2300). The maximum (design) Reynolds number was 150, which is one order-of-magnitude smaller than the transition Reynolds number. Spacing between the tubes was as small as practicable, since the tubes have to simulate the oxidizer loadings of approximately 80%.

The oxidizer in the experiments was chosen to be air for convenience. The fuel used to simulate inert binder pyrolysis

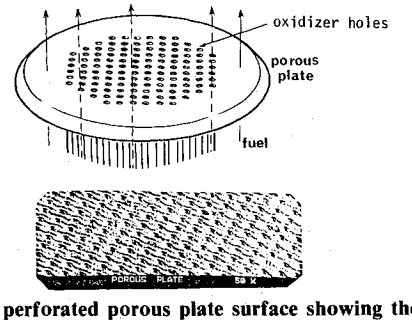

Fig. 1 The perforated porous plate surface showing the texture of the woven porous plate (below).

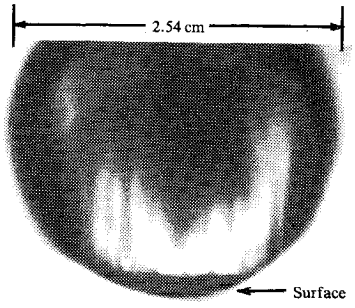

Fig. 2 The flame above the surface showing the flame standoff much like that in composite propellants. The enlarged dimensions are apparent.

products was ethane. The molecular weight of ethane is very close to the effective molecular weight of air and this is thought to minimize effects associated with intermolecular diffusion that depend on large differences in molecular weights. In the binder pyrolysis experiments (with the state-of-the-art polybuitadiene backbone) CH_2-$CH_2^{\cdot}$ have been detected in large quantities[5]; thus ethane or ethylene may be expected to be one of the principal species in the actual propellant vapors.

The experiments used a 87.5-mm diam shroud (with two 2.5-cm-diam quartz windows) over the porous plate as shown in Fig. 2. Nozzle diameters on the end wall of the shroud set the working pressure of the flame zone. Direct photography was used for flame location.

Flow oscillators were incorporated in both the fuel and the oxidizer flow lines. These are rotary valves with provision for bypass. Thus, different amplitudes of oscillations can be obtained by varying the quantity of bypass. The fuel and the oxidizer flow were oscillated synchronously. All of the experiments reported here, had all of the flow oscillated, i.e., had zero bypass. The dynamic flame position was determined through motion pictures.

Thermocouple measurements were made of the temperatures both of the porous plate (T_s), and at the surface inside the oxidizer tube (T_t). The "surface" temperature T_t was invariably higher than T_s by more than 100°C in all of the experiments; this indicates the advantage of having a surface (the porous plate) compared to cluster tube arrangements. Dynamic pressure measurements were made in the combustion chamber through a B&K microphone which had been calibrated with a 124 dB piston calibrator. The velocity fluctuation amplitudes were calculated assuming isentropic fluctuations.

Results and Discussion

Figure 3 shows that during time-independent combustion the flame standoff distance scales linearly with the reactants flow velocity independent of the mean pressure. This means that the basic flame structure, although influenced by chemical kinetics, does not vary much and that the flame is controlled by diffusion-mixing of the reactants. During oscillatory burning, if chemical kinetics do not play a key role, the relevant frequency appears to be u/X^*. If the u is held identical to that in actual propellant combustion, the characteristic frequency in the porous plate burner that matches the frequency in a propellant would be scaled down by (X^* propellant)/(X^* burner). Since the X^* is seen (Fig. 3) to be of the order of the tube diameter d as compared with $X^* \sim a$ (the oxidizer particle size) in propellants, 500 Hz frequency in a 100μ AP propellant scales down to 42 Hz in the burner. That is, the flame studies at 42 Hz in the burner can shed light on the flame details at 500 Hz in a 100μ propellant. Experiments were conducted in the porous plate burner at $u=367$ cm/s, $u'/u=0.31$, at frequencies of 0-20 Hz. The motion picture frames show that the overall flame standoff distance is identifiable and that the key flame zone at the base of flame standoff is not much affected during the

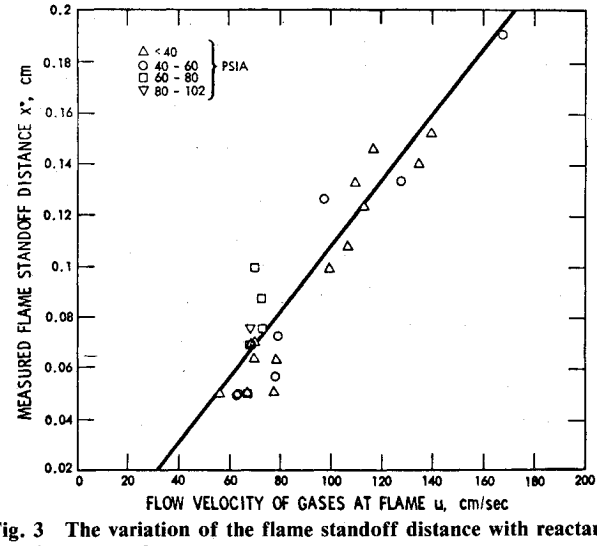

Fig. 3 The variation of the flame standoff distance with reactants' velocity at several mean pressures.

oscillations.[6] X^* fluctuates in phase with u' and the amplitude of X^* oscillations normalized by mean X^*, under these conditions, is between 0.3 and 0.2. This means that at least up to these frequencies (20 Hz in burner $\simeq$240 Hz in a 100 μm AP propellant) the vapor phase combustion continues to be controlled by the same processes (diffusion and mixing as opposed to chemical kinetics) as in time-independent combustion (Fig. 3). That is, the quasisteady vapor phase assumption that has dominated the instability theories[7] appears valid at least up to these frequencies. The experiments are presently continuing with different porous plate arrangements to model multimodal particles and different unimodal particle sizes.

Summary

1) The concept of a perforated porous plate burner appears to be valid for scale modeling the vapor phase combustion in heterogeneous propellants.

2) The flame standoff distance, which can be related to the surface heat transfer rates, depends on the mean flow velocity independent of the mean pressure during time-independent combustion.

3) The flame standoff distance varies with the flow velocity during oscillatory combustion much the same way as during time-independent combustion.

Acknowledgments

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