Criteria for Ignition in Monopropellant Engines

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Nomenclature

a = interfacial area for heat transfer, 1 m^2/ℓ
C_{PG} = gas specific heat, 60 J/mole K
C_{Ps} = solid specific heat, 1.0 J/g K
h = heat transfer coefficient, 210 J/m^2-s K
k_e = effective thermal conductivity of catalyst bed, 0.30 T_s J/m-s K
p = gas pressure, atm
R = gas constant
r_A = rate of surface reaction per unit surface area
S_A = amount of catalyst surface area per unit volume of reactor, 1.2×10^5 m^2/ℓ
T_G = gas phase temperature, K
T_S = solid temperature, K
V = gas phase velocity, m/s
x = mole fraction of monopropellant in gas
Z = axial distance along the catalyst bed, cm
ϵ = void fraction of catalyst bed, 0.5
ΔH = heat of reaction, 80 kJ/mole
ρ_G = gas density
ρ_S = solid density, 4 kg/ℓ

Introduction

HYDRAZINE-based monopropellants are a mature technology.[1] Because of suspected carcenogenity of hydrazine the feasibility of nitromethane-based monopropellants has been studied.[2,3] Nitromethane-based systems can deliver high specific impulse; but the high adiabatic decomposition temperature limits the choice of catalyst material to metal oxides that exhibit significant activation barriers for reaction, necessitating a catalyst bed preheat to function.[2] For two of the best catalysts, NiO and Cr_2O_3, a minimum catalyst bed preheat temperature for ignition was observed. Furthermore, the response time of the pressure exhaust from the catalyst bed was optimal at intermediate values of fuel flow and catalyst bed preheat.[2] In this Note we present a model that can account for those observations and provide guidelines for operation of nitromethane-based monopropellant systems.

Reactor Model

The monopropellant reactor is a packed bed catalytic reactor. The system is adequately described as an adiabatic, plug flow, two phase reactor. The transient differential equations for the reactor are given below.

$$\frac{\partial}{\partial t}\left(\frac{xP}{RT_G}\right)=-\left(U\frac{P}{RT_G}\right)_{\text{in}}\frac{\partial x}{\partial z}-(r_A S_A) \tag{1}$$

$$\frac{\partial T_G}{\partial t}=-U\frac{\partial T_G}{\partial z}+\left(\frac{ha}{\epsilon\rho_G C_{P_G}}\right)(T_S-T_G) \tag{2}$$

$$(1-\epsilon)\rho_S C_{P_S}\frac{\partial T_S}{\partial t}=(-\Delta H)(r_A S_A)$$

$$-ha(T_S-T_G)-k_e\frac{\partial^2 T_S}{\partial z^2} \tag{3}$$

$$U=U_{\text{in}}\frac{T_G}{T_{G,\text{inlet}}}(2-x) \tag{4}$$

I.G. $t<0$, $T_G=T_S=T_{\text{preheat}}$ (5)

B.C. $t=0$, $z=0$, $T_G=T_{G,\text{inlet}}$ (6)

$$x=1.0 \tag{7}$$

Homogenous reaction of nitromethane may be neglected relative to heterogeneous reaction. Homogeneous reaction is significant only above 800 K at which point ignition has already occurred. A gaseous feed was assumed as the rate of reaction is negligible below 400 K. A liquid feed would have to be vaporized and preheated to 400 K for a nitromethane-based system to function.

The rate expression for surface catalyzed reaction was that found previously for nitromethane decomposition over NiO/Al_2O_3 catalysts.[3]

$$r_A=k_S K_e xP/(1+K_e xP) \tag{8}$$

$$k_S=1.0\times10^{12}\exp(-19725/T_S)\ \text{mole/m}^2\text{-s} \tag{9}$$

$$K_e=6.1\times10^{-7}\exp(9863/T_S)\ \text{atm}^{-1} \tag{10}$$

Diffusional limitations of the reaction were included by use of an effectiveness factor. Catalyst deactivation was neglected.

The physical parameters used for model calculations are those for NiO/Al_2O_3 catalysts used in previous studies.[3] Temperature effects on the physical properties of the solid and of the heat of reaction have been neglected. The model equations were integrated using a modified finite-element method.

Results

The two performance criterion we were interested in were 1) the operating conditions for lightoff and sustained operation, and 2) the operating parameters to optimize the response time. Reactor performance was examined for three design and control parameters: fuel feed rate, feed temperature, and bed pre-heat temperature.

Only the fuel feed rate and the feed temperature are important for sustained operation. The steady state reactor model was solved to obtain the conditions on fuel feed rate and feed temperature sufficient to insure lightoff shown in Fig. 1. It should be noted that in the region in which extinction occurs, lightoff may occur by preheating the catalyst bed; however, the reaction front will creep downstream and the reaction is eventually extinguished.

Table 1 Effect of control parameters on position of combustion zone

Parameter variation	Effect on reactor performance
Increasing catalyst bed preheat	Combustion zone moves upstream toward reactor entrance
Increasing feed temperature	Combustion zone moves upstream toward reactor entrance
Increasing fuel feed rate	Combustion zone moves downstream toward reactor exit

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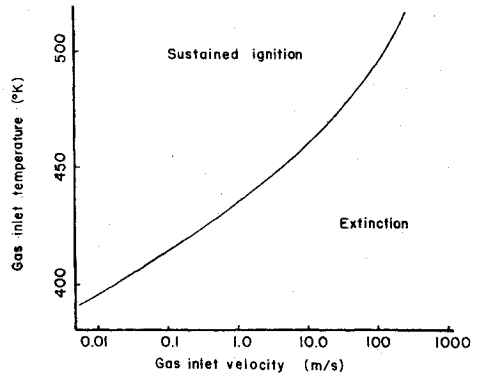

Fig. 1 Steady-state operation of reactor. Solid line represents minimum conditions to maintain sustained operation.

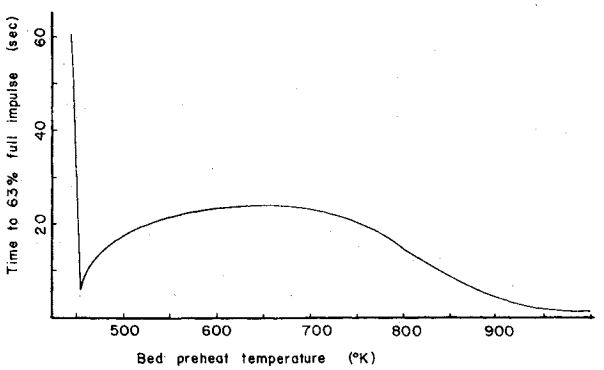

Fig. 2 Response time as a function of catalyst bed preheat: fuel feed rate = 0.6 g/s; feed temperature = 400 K.

For optimal response the exiting gas temperature should approach its steady state value as quickly as possible. Figure 2 shows results to achieve 63% of steady state impulse as a function of bed preheat for feed conditions corresponding to minimal values for sustained operation. The response time is a minimum at a moderate pre-heat temperature and increases with pre-heat temperature until very high pre-heat temperatures are introduced. At the minimum response time the ignition zone occurs at the end of the reactor. Increasing the bed pre-heat causes the reaction to move upstream. The hot combustion gases are then cooled as they heat the catalyst downstream of the combustion zone. The thermal mass of the catalyst bed is much greater than the flowing gases, slowing the desired response.

These results indicate that the optimal response is obtained when the combustion zone originates at the reactor outlet. Summarized in Table 1 are the changes the three control parameters have on the position of the combustion zone. The three parameters can be used to implement control strategies. For example, in a repetitive firing mode the response time may increase when there is insufficient time for the bed to cool to the desired temperature before the next firing. However, by increasing the fuel feed an appropriate amount the response time could be maintained constant, though the thrust would be increased.

The model presented here is able to account for the system response observed by Seifert et al. by assuming the catalyst bed is divided into two sections, a vaporization section 2 cm long and a reaction section 8 cm long. The applicability of the model suggests nitromethane-based systems with specified response characteristics are feasible, though the complexity of the control makes replacement of hydrazine-based systems unlikely.

Acknowledgment

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References

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Some New Results of Chuffing in Composite Solid Propellant Rockets

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Introduction

CHUFFING is one of the low-frequency instabilities in solid propellant rockets functioning at low chamber pressures. In chuffing, the rocket motor experiences brief spurts of combustion and consequent pressure buildup, followed by periods of near ambient pressures in the combustion chamber. This period of dormancy can extend up to a few seconds. According to many earlier workers,[1-3] during the low-pressure induction period, slow reactions take place in a subsurface layer of the propellant which eventually reaches the temperature where a thermal explosion can occur. Rapid burning of this preheated layer is followed by a sudden ceasing of propellant combustion as the layers beneath it, being at low temperature, cannot sustain the process. While this theory projects the condensed phase reactions as solely responsible for chuffing, there are also those which bring in the importance of gas phase processes.[4]

Whereas the condensed phase reactions are known to be of paramount importance in cordite-like homogeneous propellants, their importance in composite propellant combustion is still being debated. Chuffing, however, has been observed with composite propellants also.[5,6] This prompts a re-examination of the role of the gas phase processes and the motor characteristics in chuffing. Also, the data on composite propellant chuffing have not been presented in as detailed a form as with cordite propellants.[1] The present work describes systematic experimental study to relate the chuffing frequency and pressure to such rocket motor parameters as the characteristic length (L^*) and the ratio (K) of burning surface area to throat area.

Experiment

The experimental setup is similar to the one described in Ref. 6. An L^*-motor consisting of a stainless steel cylinder and a piston which can be positioned in the cylinder to provide the desired value of L^* (characteristic length = volume of the combustion chamber/nozzle throat area) is used to burn end-burning solid propellant discs (see insert in Fig. 1). A strain-gage pressure transducer and associated signal conditioner

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