Combustion and Flame 184 (2017) 90–100

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Extinction of AP monopropellant by rapid depressurization: Computational and experimental studies

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ARTICLE INFO

Article history:
Received 5 February 2017
Revised 25 May 2017
Accepted 25 May 2017

Keywords:
Ammonium perchlorate monopropellant
Extinction
Rapid depressurization
Stability

ABSTRACT

This paper presents the results of experimental and computational studies that were carried out to determine the critical depressurization rate for the extinction of ammonium perchlorate (AP) monopropellant. AP monopropellant burning at a pressure of 70 bar was depressurized to a final pressure of 25 bar, experimentally and critical depressurization rates were determined. The computational model chosen is two-dimensional in nature which couples both the gas and condensed phase and simulates the burning of an AP pellet, which had been compared extensively with experimental results available in the literature. It is found through the numerical simulations that the condensed phase plays an important role in extinction by rapid depressurization. A large amount of convective heat loss associated with the experiments was also simulated using a rudimentary convective heat loss model in the condensed phase. The critical depressurization rate determined experimentally for AP monopropellant is found to lie between 2700 and 3000 bar/s for 4.5 mm thick pellet with heat loss. The computed value for the same condition is 5000 bar/s. This indicates that there is a good match between experiments and computations.

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1. Introduction

Ammonium perchlorate/hydroxyl-terminated polybutadiene (AP/HTPB) based composite solid propellants are widely used in solid rocket motors for both launch vehicle and missile applications. The main advantages are storability, quick launch, simple design and large thrust delivering capability. The main disadvantage of solid rocket motors is its lack of flexibility after manufacture. Flexibility in total impulse delivered by solid rocket motor can be achieved by suitably terminating thrust at desired point. Controlled extinction devices need to be devised to achieve thrust termination in solid rocket motors. Solid rocket thrust termination allows the designer to dispense the liquid propellant based velocity trimming packages while still retaining the same levels of accuracy of missile systems. Rapid depressurization is one of the most attractive methods to extinguish the burning solid propellant. To achieve reliable depressurization-induced extinction, a lot of experimental and theoretical studies have been carried out on dynamic combustion characteristics of AP based composite solid propellants. A brief review of the literature on this is presented below.

In 1961 Ciepluch [1] conducted first experimental studies of depressurization transients in a laboratory combustion chamber. The actual motor conditions were closely simulated. Sudden opening of a chamber vent hole resulted in fast depressurization. Initial chamber pressure in the range of 34–82 atm and ambient pressures down to 3.5 mm of mercury were explored. Ciepluch [1] showed a minimum rate of chamber pressure decay exists to extinguish the combustion and this minimum chamber pressure decay rate increases linearly with initial chamber pressure.

Zeldovich [2] proposed a model for investigating combustion processes with constant surface temperature. In the Zeldovich model [2], the steady state burn rate dependence on initial temperature and pressure is transformed into pressure and temperature gradient at the surface. For extinction by rapid pressure decay, it was shown that if the temperature gradient exceeds its maximum value at the final pressure, combustion was impossible and the powder was quenched.

Novozhilov's [3] studies examined a model propellant with variable surface temperature during unsteady combustion processes and it was shown that such a model can be constructed by analogy with the Zeldovich theory [2]. It was recognized that with the variability of the surface temperature, the region of stable combustion increases and it is possible to predict the properties of propellants beyond the (Zeldovich [2]) stability limit. But the basic region for extinction due to rapid pressure decay was similar to Zeldovich model [2].

Merkle et al. [4] emphasized on the pressure–time curve for dynamic extinction and furnished a new quasi steady flame model. They pointed the incorrect use of quasi steady gas phase

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http://dx.doi.org/10.1016/j.combustflame.2017.05.030
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Abbreviation

AP	Ammonium Perchlorate (NH_4ClO_4)
APD	Final decomposition products of AP combustion obtained from chemical equilibrium calculations
APP	Final decomposition products of AP (NH_3(gas)+$HClO_4$ (gas))
HTPB	Hydroxyl-Terminated PolyButadiene
LPDL	Low Pressure Deflagration Limit
QSC	Quasi Steady Condensed phase

Nomenclature

A_{DB}	Denison-Baum parameter
A_g	pre-exponential factor in the gas phase reaction
A_s	pre-exponential factor in the surface pyrolysis law
C_{pc}	specific heat of condensed phase
C_{pg}	specific heat of gas phase
E_g	activation energy in the gas phase reaction
E_s	activation energy in the surface pyrolysis law
H_{fAP}	heat of formation of AP
H_{fAPD}	heat of formation of APD
H_{fAPP}	heat of formation of APP
H_L	heat loss per unit volume for individual condensed phase cell
H_r	heat of reaction
p	pressure
P_i	initial pressure
P_f	final pressure
Q_s	heat of pyrolysis
R	characteristic gas constant
$\bar{R}$	universal gas constant
T	temperature
T_f	flame temperature
T_s	surface temperature
$T_{-\infty}$	far field temperature in ap slab, ambient temperature
Y_i	the AP combustion mass fraction of the ith species
Y_{i0}	mass fraction of the ith species at the surface
Y_{iv}	mass fraction of the ith species in the pyrolysis products
d	strand hydraulic diameter
f	fraction of AP decomposing at the surface
h	convective heat transfer coefficient
k_c	condensed phase thermal conductivity
k_g	gas phase thermal conductivity
$\dot{r}_n$	burn rate normal to the regressing surface
t	time
u	velocity in the x-direction
$\hat{u}_0$	velocity of the gases at the regressing surface normal to it
v	velocity in the y-direction
x	coordinate above regressing surface
$\hat{x}$	direction normal to the regressing surface
y	coordinate along the thickness
α_{DB}	Denison-Baum parameter
$\mathcal{D}_i$	diffusivity of ith species
ε	Denison-Baum parameter
$\mathcal{M}$	molecular weight
μ	molecular viscosity of the gases
ρ_c	density of condensed phase
ρ_g	density of gas phase
τ	time taken to reach steady state
$\dot{w}'''_i$	reaction rate associated with ith species
$\dot{w}'''$	overall reaction rate

assumption in the theoretical work done by various researchers like Von Elbe and Machale [5], Paul et al. [6], Horton et al. [7] and Ryan et al. [8]. It was argued that for extinction by rapid depressurization the temperature profile in the solid must be non-steady. Thus, the heat feedback from the quasi steady gas phase to the non-steady solid must be non-steady. However, no criterion for extinction was formulated. A critical value for surface temperature ($T_s = 600$ K) was empirically chosen for simulations. Chemical reactions were considered too weak to sustain deflagration waves below this temperature. This extinction surface temperature was supposed to be a function of propellant as pointed by T'ien [9].

Studies by T'ien [9] in 1974 were aimed directly at establishing an extinction criterion for fast depressurization. T'ien [9] attributed heat loss from the flame as the mechanism for both static and dynamic extinction of solid propellants.

Mongia and Ambs [10] recognized the finite time associated with the condensed phase heat release. It was also argued that condensed phase heat release depends on the instantaneous properties near the burning surface and condensed phase reactions were emphasized.

Donde et al. [11] used a laboratory combustion chamber with a much larger exhaust chamber connected by double diaphragm system. The small space between the two diaphragms was pressurized to a pressure nearly half of the combustion chamber pressure. The pressure post depressurization can be controlled by controlling the pressure in the exhaust chamber. The experiments were performed with initial pressure ranging from 4 to 31 atm and final pressure 1 or 3.25 atm.

De Luca [12] has authored a good review article on the literature on extinction by rapid depressurization studies carried out by various researchers up to late 80′s. De Luca [12] has emphasized on the difference between the static and dynamic burning stability. It was argued that both the static and dynamic limits overlap near the Pressure Deflagration Limit (PDL). De Luca [12] also concurs with Merkel et al. [4] that there is a minimum value of surface temperature below which extinction of burning propellants necessarily follows.

Steinz and Selzer [13] examined extinction of AP based composite propellant by depressurization experimentally and observed the flame structure, surface characteristics and restart capability. It was found that the for sufficiently large depressurization rate (>16000 atm/s) for an initial pressure of 45 atm, the flame is quenched immediately. However, for the depressurization rate between 7500 and 16000 atm/s a new flame was observed to develop which quenches when pressure equilibrates with the final pressure of 1 atm. It was pointed out that the decomposition of AP monopropellant plays an important role during depressurization. A general statement was made that the extinction occurs due to lack of necessary gaseous reaction heat sources during depressurization.

In 2002, Anil Kumar and Lakshimsha [14] recognized the error caused by the assumption of quasi steady condensed phase degradation zone (QSC), when the surface temperature fluctuates with large amplitudes. The proper variation of thermo-kinetic properties as a function of instantaneous pressure was stressed as the key to obtain quenching during rapid depressurization.

All the above work has given some insight into the process of extinction of solid composite propellants by rapid depressurization. But a more insightful understanding of what actually happens during a depressurization process is still missing. This paper aims to bridge this gap. Following Steinz and Selzer's [13] comment of AP monopropellant could be playing an important role, as a precursor to understanding the extinction processes in the composite solid propellant here the focus will be on AP monopropellant extinction by rapid depressurization. The paucity of literature on AP extinction by rapid depressurization was the motivation for undertaking this study. Here, both experimental and computational routes are

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