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Pulse Triggered Ci In SRMs: A Comprehensive Review of Nitramine, Aluminum and AP Particle Size

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Abstract

Pulse-triggered combustion instability in solid rocket motors (SRMs) arises from nonlinear coupling between unsteady heat release and chamber acoustics when a finite-amplitude perturbation, such as a pressure pulse, drives the system beyond its stability threshold. Over the past several decades, theoretical, numerical, and experimental studies have shown that triggering behaviour depends not only on chamber geometry and operating conditions but also on the detailed combustion response of the propellant, which is strongly influenced by nitramine content, aluminium loading, and ammonium perchlorate (AP) particle size. Nitramine oxidizers (RDX, HMX) modify burning rate, pressure exponent, and transient response, often increasing the pressure-coupled gain, while aluminium particles introduce two-phase effects that can either damp or drive instability depending on loading and agglomeration behaviour. AP particle size controls flame structure, burning rate, and low-frequency coupling, thereby shaping the overall stability landscape. This review synthesizes key developments in pulse-triggered instability theory, experimental methodologies for pulsed testing, and the documented influences of nitramine content, aluminium content, and AP particle size on combustion stability, with emphasis on their integrated impact on pulse-triggered behaviour in SRMs.

1. INTRODUCTION

Combustion instability in solid rocket motors manifests as self-excited pressure oscillations that can produce DC pressure shifts, elevated thermal and mechanical loads, and, in severe cases, structural failure. While classical linear stability analyses address small-amplitude acoustic oscillations, many practical SRMs exhibit nonlinear axial modes characterized by steep-fronted, shock-like pressure waves and large mean-pressure increases, necessitating nonlinear gas dynamic treatments. Pulse-triggered instability, in which a finite-amplitude pressure disturbance initiates sustained oscillations in an otherwise linearly stable system, is now recognized as a critical design driver for high-performance SRMSRMs operate under extreme conditions, characterized by high pressures, temperatures, and transient loads. One of the most significant challenges in their operation is combustion instability (CI), which manifests as self-sustaining oscillations in chamber pressure. These oscillations, if left uncontrolled, can lead to increased thermal and mechanical loads, loss of performance, and catastrophic motor failure. The phenomenon is complex, arising from a coupling of acoustic modes, unsteady combustion dynamics, and flow interactions

within the chamber. CI can occur in various frequency ranges, including low, intermediate, and high frequencies, each driven by distinct mechanisms.

Early case studies on large motors such as Titan, space shuttle SRBs, and Ariane 5 highlighted the operational consequences of unsteady combustion, including DC shifts and abrupt changes in thrust and guidance loads. Subsequent theoretical work established that the onset and limit-cycle behavior of instability depend on the interplay among chamber acoustics, mean flow, and the propellant's pressure-coupled response function, which encodes how burning rate responds to pressure fluctuations. Against this backdrop, the formulation space—including nitramine, aluminum, and AP characteristics—has emerged as a central lever by which designers can tune both performance and stability, particularly under pulse-triggered conditions.

This paper aims to provide a comprehensive review of pulse triggered CI in SRMs, exploring its historical context, mechanisms, and the effects of nitramine, aluminium and AP particle size in stability of the motor.

2. PULSE TRIGGERED COMBUSTION INSTABILITY

2.1.Nonlinear triggering theory

Levine and Baum developed the first comprehensive framework for pulse-triggered instability in solid rocket motors, demonstrating that finite-amplitude pressure pulses can push a nominally stable system into a nonlinear limit cycle. Their analyses, complemented by numerical simulations, showed that the triggering threshold depends on the acoustic mode structure, mean flow, and nonlinear combustion response, rather than solely on linear stability margins. Subsequent work extended these ideas to include mode interaction and multi-frequency coupling, leading to predictions of complex oscillatory patterns once the threshold is exceeded.

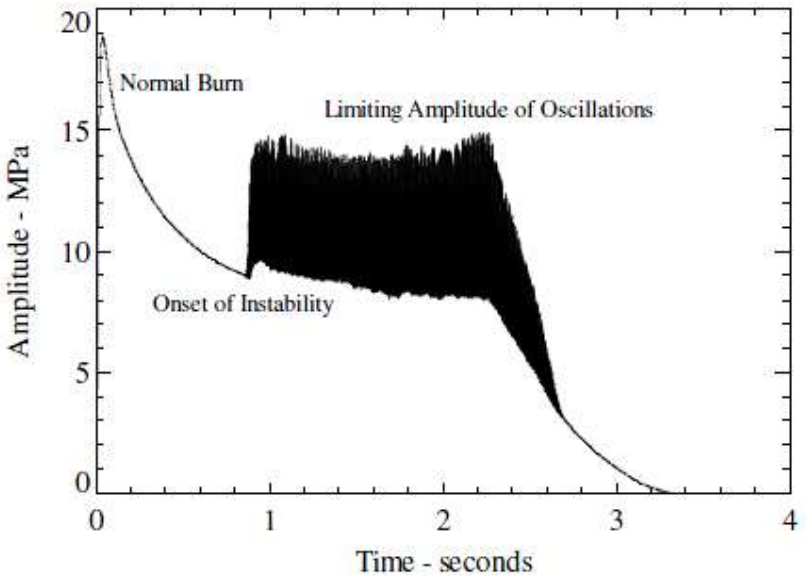

Fig. 1: Nonlinear limit cycles with DC shift

DC Shift: Direct current (DC) shifts denote sustained changes in the mean chamber pressure arising from nonlinear coupling between acoustic oscillations and combustion processes. Unlike purely oscillatory instabilities, which fluctuate about a fixed mean pressure, DC shifts produce a persistent increase or decrease in the average pressure level. Such shifts can further destabilize the motor by modifying the

feedback mechanisms linking unsteady heat release and pressure fluctuations. In regimes dominated by high-amplitude nonlinear instabilities, the direction and magnitude of the mean pressure shift depend strongly on the phase relationships between the pressure field and combustion response. DC shifts therefore pose a significant challenge to motor stability, as they can degrade combustion efficiency, alter operating conditions, and potentially induce structural overstressing or failure.

Limit Cycle: Limit cycles describe a nonlinear steady-state regime in which pressure oscillations attain a finite, constant amplitude. This state arises when the energy supplied by unsteady combustion exactly balances the energy dissipated through mechanisms such as nozzle damping, particle–gas interactions, and boundary layer losses. Although the oscillation amplitude ceases to grow, the persistence of these oscillations can remain highly detrimental to motor performance and structural integrity. A defining characteristic of limit cycles is their stability: small disturbances neither amplify nor attenuate the oscillations but instead decay back to the established cycle. In solid rocket motors, limit cycles commonly appear as sustained pressure oscillations that can promote mechanical fatigue, particularly in the motor casing and nozzle regions. The resulting oscillation amplitude is governed by the nonlinear balance between acoustic energy generation and dissipation.

Waveform Distortion: In the presence of nonlinear combustion instability, pressure oscillations depart markedly from the sinusoidal waveforms predicted by linear stability theory. These deviations are characterized by distorted pressure traces exhibiting sharp peaks, asymmetry, and a broadened frequency spectrum. Such non-sinusoidal behavior originates from nonlinear feedback effects that selectively amplify certain acoustic components while attenuating others. For instance, a pressure waveform may display rapid pressure rises followed by more gradual decays, reflecting an uneven redistribution of energy across harmonics and frequency bands. These waveform distortions complicate both the prediction and control of instability, as they introduce higher-order harmonics and sidebands into the spectral response. In solid rocket motors, distorted pressure oscillations can intensify structural vibrations and promote non-uniform erosion of the motor casing or nozzle, thereby compromising mechanical integrity.

Yang, Kim, and Culick formalized the role of nonlinear gas dynamics in the growth and saturation of longitudinal pressure oscillations. Using higher-order acoustic equations, they showed that steepening of acoustic waves and the associated DC pressure shift are intrinsic features of nonlinear wave propagation in combusting flows, with pressure amplitudes often reaching 20% of the mean chamber pressure in full-scale SRMs. Wicker et al. later coupled these nonlinear gas dynamic models with detailed combustion response functions, demonstrating that the phase and gain of the pressure-coupled response at the motor's natural frequencies govern whether a given pulse decays or grows into sustained instability. Culick's second-order nonlinear acoustic theory provided a compact description of limit-cycle amplitudes and clarified why small differences in damping can yield large changes in final oscillation levels. This framework also explained the experimentally observed DC shifts as a consequence of enhanced propellant burn rate in the presence of strong oscillatory flow parallel to the burning surface. Later analyses by Flandro and co-workers expanded these concepts to include velocity-coupling and vortex-shedding mechanisms, linking shear-layer dynamics and mean-flow modification to triggering and saturation behaviour.

2.2. Pulse Testing Methodologies

Finite-amplitude pulses in SRMs arise naturally from transient events such as partial nozzle blockages by ejecta, igniter debris, or broken propellant chunks, motivating the development of controlled pulsed testing techniques. Early pulser systems employed pyrotechnic "bombs" and piston devices to generate

repeatable pressure pulses, enabling parametric studies of pulse amplitude, duration, and timing on motor response. More recent designs include ejecta pulsers that launch solid spheres through the nozzle, closely emulating in-flight partial throat blockages and providing well-characterized pulse amplitudes based on simple nozzle-flow models.

Lovine and co-workers derived a one-dimensional isentropic model for predicting the pulse amplitude generated by ejecta passing through the nozzle throat, highlighting the role of throat area blockage fraction and constriction ratio. Comparisons between predicted and measured pulse amplitudes show good agreement for moderate blockage, but significant deviations for larger ejecta, where non-isentropic effects and complex flow separation become important. Experimental campaigns have established that for a given motor and propellant, there exists a critical pulse amplitude (or equivalently, a critical ejecta size) below which the system remains stable, at which transient excitation decays, and above which sustained nonlinear instability is triggered.

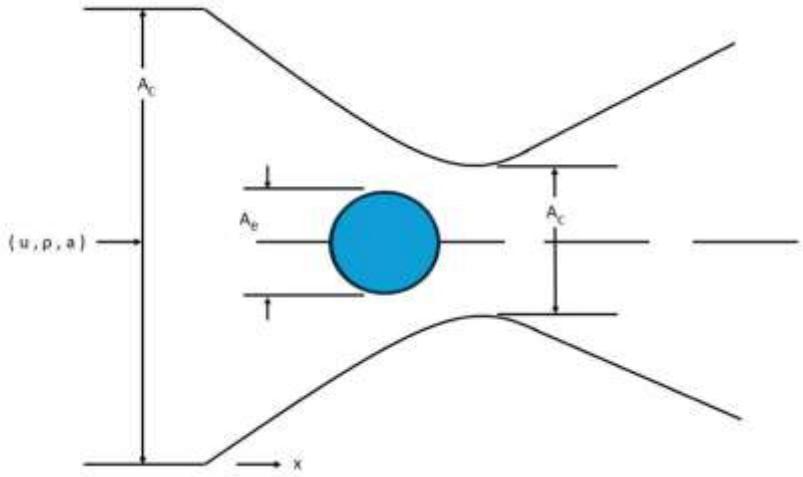

Fig. 2: Schematic of Ejecta Blocking the nozzle

Pressure pulses in solid rocket motors originate from ejecta exiting the motor through the nozzle, temporarily restricting the flow area. Therefore, estimating the maximum pulse amplitude that can occur during motor operation is essential for assessing combustion stability. Lovin *et al.* proposed a simplified analytical model to predict the pressure pulse amplitude generated by such ejecta.

The model assumes one-dimensional, isentropic flow through the nozzle and considers the ejecta-induced disturbance as a transient reduction in the effective throat area. Under these assumptions, and employing linear wave propagation theory together with a quasi-steady nozzle approximation, the pulse amplitude can be expressed in terms of the nozzle geometry and the degree of flow blockage.

The resulting expression for the normalized pressure pulse amplitude is given by:

$$\frac{p_1 - p}{p_1} = \frac{\delta p}{p_1} = \left[\gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right] f_b J$$

where δp is the pressure perturbation, p_1 is the undisturbed chamber pressure, γ is the ratio of specific heats, J is the initial constriction ratio defined as the ratio of throat area to nozzle entrance area, and f_b represents the fraction of the throat area blocked by the ejecta.

This relationship indicates that the pulse amplitude scales linearly with both the initial constriction ratio and the blockage fraction, highlighting the dominant influence of nozzle geometry and ejecta size. The quasi-steady nozzle assumption is most valid for slow-moving ejecta and is known to overpredict pulse amplitudes for smaller, high-velocity particles. Consequently, lower pulse amplitudes are typically associated with fast-moving ejecta, which produce short-duration pulses on the order of 0.2–0.4 ms.

A key limitation of the ejecta pulsing approach arises from geometric constraints: the cross-sectional area of the ejecta must be smaller than the minimum port and grain cross-sectional areas to avoid impingement on the propellant surface. Among the parameters governing pulser performance, the ejecta cross-sectional area and its initial velocity are the most influential.

Although ejecta pulsing is a powerful diagnostic tool for evaluating motor stability, many operational motors are not deliberately pulsed, often due to cost considerations or the assumption that a motor exhibiting stable behaviour under nominal conditions will remain stable in service. However, neglecting the motor's response to pressure pulses may be risky, as even relatively small pulse amplitudes can significantly alter combustion dynamics and trigger instability.

Blomshield and collaborators compiled extensive databases of pulse-triggered tests in subscale and full-scale motors, documenting growth rates, frequency spectra, and DC shifts as functions of pulse characteristics and operating conditions. These data sets have been instrumental in validating nonlinear stability models and in demonstrating that motors can be linearly stable yet nonlinearly unstable when subjected to sufficiently strong pulses. More recent work combines pulsed firing with high-speed diagnostics and advanced signal processing to resolve multi-mode interactions and non-normal amplification phenomena in SRMs.

In addition to ejecta-based pulsers, several other pulsing devices have been developed to introduce controlled pressure disturbances in solid rocket motors; a brief description of these devices is presented below.

Explosive Bombs:

Explosive bombs consist of small pyrotechnic charges that are detonated at predetermined times within the motor. The detonation generates a sharp pressure pulse inside the combustion chamber, and the motor's response to this disturbance is subsequently analyzed to assess stability characteristics. A major drawback of this technique is that the presence of the charge can disturb the normal chamber flow field prior to detonation, potentially influencing the baseline combustion behavior.

Low Brisance Pulser:

In a low-brisance pulser, a pyrotechnic charge is ignited, causing a gradual rise in pressure that leads to the rupture of a diaphragm, as illustrated in the figure. The pressure generated by the expanding combustion products acts on the base of a piston, driving it backward and initiating the opening of a vent. As the piston traverses the vent opening, the combustion gases are discharged through the vent and injected into the motor chamber, thereby producing a pressure pulse.

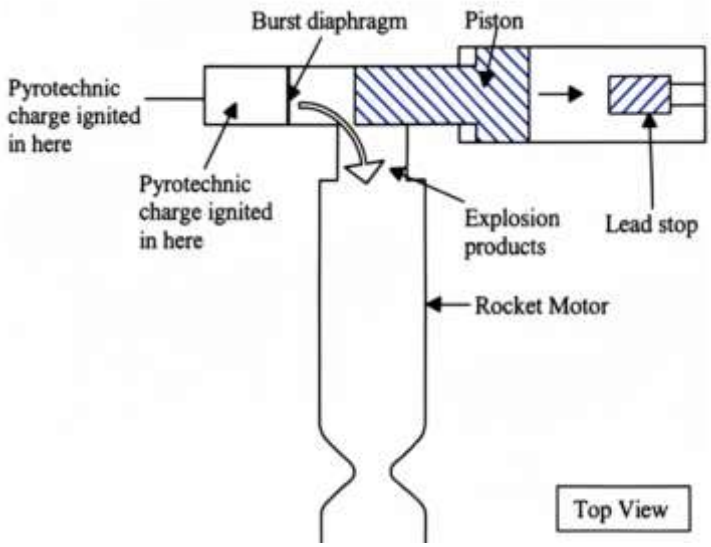

Fig. 3: A schematic of Low-Brisance Pulser

One limitation of this device is the potential introduction of foreign particles into the operating combustion chamber. In addition, the external flow entering through the pulser can distort the core flow pattern within the chamber, which may complicate the interpretation of stability measurements.

Pyro Pulser:

In a pyro pulser, ignition of a pyrotechnic charge causes a rapid pressure rise in a driver volume, resulting in the rupture of a burst diaphragm. Once the diaphragm ruptures, the combustion products along with any remaining unburned pyrotechnic material expand into the pulser channel and are vented into the combustion chamber. The magnitude of the pressure pulse generated by this device depends on several factors, including the mass of the pyrotechnic charge, the motor operating pressure, and the available free volume of the motor chamber.

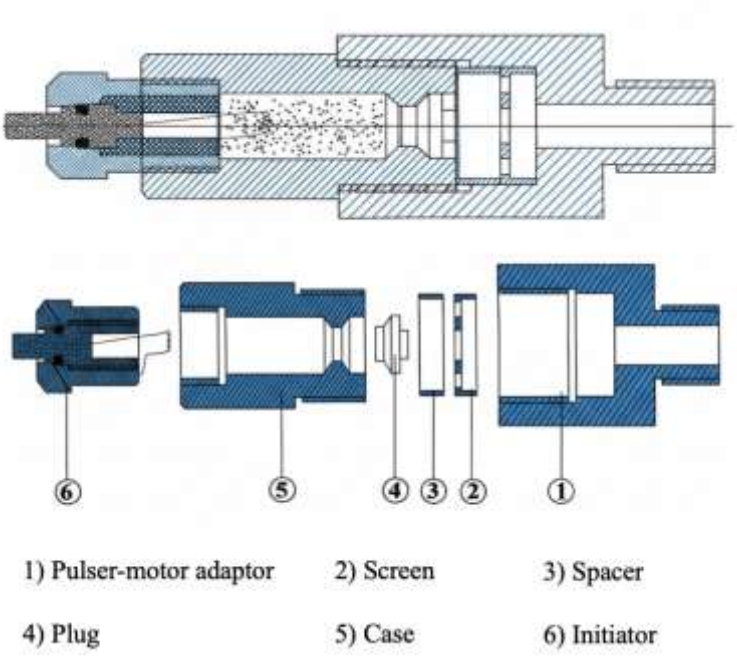

Fig. 4: A schematic of a Pyro Pulser

In practice, the expansion of the resulting shock wave within the motor chamber is a highly complex and chaotic process involving hot pulse gases. The shock does not immediately evolve into a planar traveling wave; rather, this transition occurs only after propagating several chamber diameters downstream. Consequently, the initial pressure amplitude measured by a transducer is typically much smaller than that observed during the first reflection of the traveling wave. This initial measured amplitude is therefore regarded as the effective pulse amplitude. The decay of the pulse amplitude follows an approximately exponential trend, implying that the actual disturbance experienced by the motor is often lower than the nominal or calculated pulse amplitude expected from a pyro pulser.

3. NITRAMINE CONTENT AND PARTICLE SIZE EFFECTS

3.1.Combustion characteristics of nitramine propellants

Nitramine-containing propellants, particularly those formulated with RDX or HMX, offer high energy density and low smoke, but they markedly alter combustion behavior relative to conventional AP-based systems. Kubota and others showed that nitramine composite and double-base propellants exhibit distinct flame structures with multi-stage condensed-phase decomposition and prominent dark zones, leading to higher pressure exponents and altered sensitivity to pressure fluctuations. Beckstead's mechanistic studies indicated that gas-phase reactions of nitramine decomposition products introduce strong pressure-coupled feedback, often increasing the gain of the combustion response function

Experimental investigations on advanced nitramine-based propellants have reported that increasing nitramine content generally increases burning rate and can raise the pressure exponent, particularly at low and intermediate pressures. At the same time, binder system and co-oxidizer selection (e.g., AP in NEPE and CMDB formulations) can moderate these trends, with partial replacement of AP by nitramines sometimes reducing pressure exponent while maintaining or improving performance. Ballistic modification studies show that small AP additions to minimum-signature nitramine formulations can smooth pressure-time histories and reduce instability issues associated with purely nitramine-based compositions.

3.2.Pressure coupled response and instability

Nitramine-rich formulations often exhibit strong pressure-coupled response, making them more sensitive to both self-excited and pulse-triggered instabilities than comparable AP-only propellants. Early NASA and JANNAF studies on smokeless nitramine propellants demonstrated higher response function amplitudes and more frequent occurrence of limit cycles in T-burner and motor tests, especially in the 1–5 kHz range. Smith and Beckstead quantified the transient combustion response of nitramine-based propellants, showing that the phase of the response shifts with pressure and composition in ways that can either stabilize or destabilize specific acoustic modes.

More recent numerical simulations of NEPE and other nitramine-plasticized propellants have revealed that nitramine content modulates the coupling between flame dynamics and chamber acoustics, with higher nitramine loading often lowering the threshold pulse amplitude required to trigger instability. Pulsed testing campaigns have confirmed that nitramine-rich compositions exhibit larger oscillation amplitudes and more pronounced DC shifts in response to identical pulses compared to nitramine-free baselines, underscoring the importance of nitramine content in nonlinear stability margins.

3.3.Nitramine particle size effects

Particle size adds another layer of control over nitramine combustion behavior and stability. Kubota and co-workers demonstrated that reducing HMX particle size increases burning rate and modifies pressure

exponent, with finer particles generally producing higher exponents and stronger low-frequency response. Studies on RDX- and CL-20-based composites have shown that finer nitramine particles yield more compact flame zones and higher concentrations of reactive intermediates, enhancing sensitivity to pressure oscillations and reducing response times.

Transient studies under rapid heating conditions indicate that smaller nitramine particles exhibit faster ignition and burning-rate response to pressure perturbations, thereby increasing the effective combustion response gain at acoustic frequencies. At the same time, particle agglomeration behavior can counteract some of these effects; smaller primary particles may coalesce into larger aggregates during combustion, altering the effective burning surface and modulating the overall response. The net impact on pulse-triggered instability thus depends on both primary particle size and in-situ agglomeration dynamics, making detailed characterization of nitramine size distributions essential for stability assessments.

4. ALUMINIUM CONTENT AND PARTICLE SIZE EFFECTS

4.1.Aluminium as a performance and stability modifier

Aluminum is widely used in SRMs to increase specific impulse and combustion temperature, but its multiphase combustion introduces complex effects on stability. Classical viewpoints emphasized aluminum's role as a stabilizing agent at high frequencies, where particle inertia and heat capacity provide significant acoustic damping. However, more recent studies have shown that under certain conditions aluminum combustion can drive instability, particularly at low and intermediate frequencies.

T-burner and motor experiments comparing aluminized and non-aluminized propellants have demonstrated that aluminum can contribute a net destabilizing term in the stability balance, depending on loading level and agglomeration behavior. When aluminum loading is low (e.g., 1–3 wt%), the damping effect often dominates, whereas at higher loadings (e.g., >15 wt%) unsteady aluminum combustion and droplet burning can provide strong heat-release fluctuations that couple positively with pressure oscillations.

4.2.Aluminium combustion – acoustic coupling

Recent work has established that aluminum combustion can, by itself, drive longitudinal instabilities in SRMs. T-burner studies have shown that aluminized propellants exhibit a strong negative stability margin, while identical non-aluminized formulations remain stable, confirming that aluminum combustion constitutes a primary source of gain in some systems. Numerical and experimental analyses of aluminum droplet combustion in acoustic fields reveal that the phase relationship between droplet burning rate and pressure oscillations controls whether aluminum acts as a net driver or damper.

Heat release rate fluctuations from aluminum combustion are particularly important near frequencies where droplet response times are comparable to acoustic periods, leading to resonant amplification. At higher frequencies, droplet inertia and finite heat-transfer times tend to produce phase lags that enhance damping, consistent with the long-standing observation that aluminum often stabilizes high-frequency instabilities. These competing mechanisms suggest that the impact of aluminum on pulse-triggered instability is configuration-dependent, with a strong sensitivity to frequency, loading, and chamber conditions.

4.3.Aluminium particle size and agglomeration

Particle size and agglomeration behavior significantly influence aluminum's role in combustion instability. Experiments on composite propellants with varying aluminum particle sizes show that finer aluminum tends to increase burning rate and pressure exponent, enhancing pressure-coupled gain and

potentially destabilizing the system. Conversely, larger particles ignite more slowly and burn longer in the gas phase, sometimes reducing near-surface feedback but increasing two-phase losses and plume radiation.

Agglomeration at the burning surface produces aluminum-rich melt pools and large oxide agglomerates that alter both mean-flow and unsteady behavior. Reviews of agglomeration phenomena indicate that particle size distribution, binder rheology, and AP particle size all strongly affect agglomerate size, which in turn controls droplet residence time and acoustic coupling. Recent studies highlight that suppressing excessive agglomeration—through formulation changes or tailored aluminum morphology—can mitigate aluminum-driven instabilities without sacrificing performance.

5. AMMONIUM PERCHOLORATE PARTICLE SIZE EFFECTS

5.1.Burning rate and pressure exponent control

AP remains the primary oxidizer in most composite SRMs, and its particle size distribution is a first-order design variable for both ballistic and stability performance. Foundational work on composite propellants showed that reducing AP particle size increases burning rate and often the pressure exponent, particularly for bimodal blends with fine and coarse AP fractions. These changes directly influence the pressure-coupled combustion response, with higher exponents generally producing larger response gains and increased instability susceptibility.

Strand, Cohen, and Price quantified the relation between AP size, burning rate, and pressure-coupled response, showing that finer AP shifts the response function upward in magnitude and can alter the phase at key acoustic frequencies. Subsequent experimental and numerical studies have confirmed that AP size also affects ignition transients and surface regression behavior under oscillatory conditions, thereby shaping both low- and high-frequency response.

5.2.Pressure coupled response and instability

AP particle size influences not only steady burning but also the transient response to pressure perturbations. Studies on pressure-coupled instability in AP-based propellants show that finer AP often leads to higher response amplitudes and lower damping, increasing the likelihood of both self-excited and pulse-triggered oscillations. Transient heating models indicate that smaller AP particles respond more quickly to temperature and pressure fluctuations, amplifying the effect of acoustic waves on burning rate.

Recent work on NEPE and similar composite systems has demonstrated that combined variation of AP and aluminum particle sizes significantly affects combustion product distributions and two-phase flow properties, including agglomerate size distributions and plume structure. These changes feed back into acoustic damping and driving, making AP particle size a crucial parameter in the global stability balance, especially when combined with nitramines and aluminum.

6. INTERGRATED EFFECTS ON PULSE TRIGGERED CI

Pulse-triggered instability in modern SRMs emerges from the coupled influence of nitramine content and size, aluminum loading and size, and AP particle size, all operating within a nonlinear acoustic environment. Nitramine oxidizers tend to increase pressure-coupled gain and modify flame structure, aluminum introduces frequency-dependent driving and damping through two-phase combustion, and AP size sets the baseline burning-rate sensitivity and transient behavior.

Integrated experimental and numerical studies on advanced composite and NEPE propellants show that particular combinations of high nitramine content, moderate-to-high aluminum loading, and fine AP can substantially lower the threshold pulse amplitude required to trigger instability, while also increasing DC shifts and peak pressure levels once instability is established. Conversely, formulations using moderate nitramine content, carefully controlled aluminum loading and agglomeration, and tailored AP size distributions can achieve high performance with acceptable nonlinear stability margins under pulsed conditions.

From a design standpoint, the literature suggests that robust SRMs resistant to pulse-triggered instability should be formulated to limit pressure exponent, control nitramine-driven response gains, and manage aluminum-driven thermoacoustic coupling through both loading and particle engineering, while using AP size distributions that avoid excessively high transient sensitivity. Achieving this balance requires integrated testing and modeling—combining pulsed firing, T-burner measurements, and high-fidelity simulations—to map stability boundaries in the multi-dimensional formulation space.

7. CONCLUSION

The literature on pulse-triggered combustion instability in SRMs demonstrates that finite-amplitude pressure pulses can induce sustained nonlinear oscillations in motors that may appear stable under small-signal analyses, highlighting the importance of nonlinear gas dynamics and combustion response functions in stability assessment. Nitramine content and particle size strongly influence burning rate, pressure exponent, and transient response, often increasing pressure-coupled gain and modifying flame structure in ways that lower triggering thresholds. Aluminum content and particle size introduce competing damping and driving effects through two-phase combustion, with agglomeration behavior playing a central role in determining whether aluminum stabilizes or destabilizes the system. AP particle size further shapes burning-rate sensitivity and transient response, thereby modulating both low- and high-frequency stability characteristics.

Taken together, these findings underscore that pulse-triggered instability is a multi-parameter phenomenon in which propellant formulation—through nitramine, aluminum, and AP characteristics—interacts intimately with chamber acoustics and mean flow. Future work identified in the literature emphasizes the need for integrated experimental–computational frameworks capable of simultaneously resolving gas-phase, condensed-phase, and two-phase dynamics under pulsed excitation, enabling more reliable prediction and control of nonlinear instability in next-generation SRMs.

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