HETEROGENEOUS PROPELLANT INTERNAL BALLISTICS: CRITICISM AND REGENERATION

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Although heterogeneous propellant and its innately *non-deterministic* morphology dominate applications, idealized homogeneous propellants *determinism* rules ballistic characterization and internal ballistics. Unfortunately, boundary value problem fundamentals, philosophical principle, and open literature demonstrate this dichotomy prohibits robust predictions for and “deep understanding” of heterogeneous propellant grained applications. Moreover, continuing absence of these perspectives from peer reviewed and/or edited publications infers idealized homogeneous propellant is a Kuhnian paradigm that inhibits research and corrupts solid rocket education. Engineering practice based on detailed simulations and adroit experimental characterizations potentially ameliorates the paradigm’s technical concerns; publications with adequate perspective would mitigate education’s.

1 INTRODUCTION

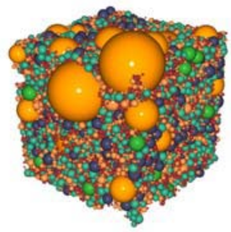

Fig 1 Propellant Packing

Solid propellant applications are dominated by heterogeneous propellants’ [1,2] and their innately *non-deterministic* (they are well mixed), poly-disperse, chemically discrete morphology e.g. Fig. 1 and [3] – and this dominance is expected to continue [4]. However, ballistic characterization [5-7`] and internal ballistics have always been ruled by idealized homogeneous propellants’ *determinism.* Therefore, because a deflagration wave expands the solid phase’s morphology, unless its condensed phase’s processes ameliorate the virgin propellant’s e.g. Kubota’s [8] polyurethane, RDX propellants, gaseous products from a heterogeneous propellant deflagration wave’s burning surface (BS) are typically *non-deterministic* in space and time at the oxidizer particles’ micro-scale in an isobaric, quiescent environment. Consequently, because the set of heterogeneous propellants (non-deterministic processes) contains idealized homogeneous propellants (deterministic processes) but the converse is false, Einstein’s statement of Occam’s Principle of Parsimony [9]

“*Every theory should be as simple as possible but not simpler*”

infers idealized homogeneous propellant’s deterministic models are “too simple” for heterogeneous propellants and fantasies should be expected. Moreover, since general field equations governing condensed phase and flowfield e.g. the Navier-Stokes equations

$$\rho D\vec{u} / Dt = -\nabla p - \nabla \vec{\tau} + \rho \vec{g} \quad (1)$$

apply to either deterministic or non-deterministic boundary conditions (BCs), deterministic BCs prohibit robust predictions for heterogeneous propellant grained applications – insufficient BC information. Ergo, basic philosophical principle and boundary value problem fundamentals infer internal ballistic’s non-deterministic propellant, deterministic theory dichotomy precludes robust predictions for and “deep understanding” of heterogeneous propellant grained applications.

The above infers internal ballistic theory and idealized homogeneous propellant burning rate models’ [10], the BDP genre [11-16] of heterogeneous propellant burning rate models, burning rate data†, and

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† Ballistic characterization does not provide explicit deterministic information.

all models based on burning rate data e.g. $r_b = a_T p^n$, ZN models [17], and erosive burning models [18] – are impotent for robust flowfield predictions of heterogeneous propellant grained applications. Moreover, because this dichotomy is present without perspective to the challenges above in texts [19,20], monographs [21-23], the AIAA's Progress Series [24-27], and peer and editor reviewed publications (see below), it is a Kuhnian paradign [28] that intellectually inhibits education, research, and application development. For example, because idealized homogeneous propellant theory does not require explicit non-deterministic information, research to that end is unjustified and does not occur.

The *Rocfire* Code's detailed simulations of heterogeneous propellant deflagration visualizes non-deterministic aspects and enables qualitative assessments of consequences [29]. Figure 2 presents an instantaneous tomogram of the temperature field‡ for a heterogeneous propellant deflagrating in a quiescent, isobaric environment with $y_i, i = 1 \ldots 25$ varying from panel to panel. Figure 3 presents temperature, time histories for ideal micro-thermocouple's in this field. In contrast, for idealized homogeneous propellants each panel of Fig. 2 would have a uniform temperature and that temperature would increase monotonically from panel to panel with increasing altitude y. Moreover, all of Fig.3's temperature, time histories would be monotonically increasing and congruent. Therefore, Figs. 2's and 3's complexities illustrate that heterogeneous propellants' non-deterministic morphology significantly impacts BS BCs and near BS phenomena.

Figure 2 demonstrates equilibrium, typically assumed to occur by ~30μm altitude [30], is incomplete at 1500μm i.e. almost two orders of magnitude beyond expectations – supported by Povinelli's [31] CN spectra, Korobeinichev's [32] micro-thermocouple measurements (contrast his Fig. 12 with Fig. 3), and [33]'s schlieren images. Moreover, Fig. 2's transverse density (and composition) gradients (see [33]'s schlieren images) from BS to beyond 1.5mm, that are absent for idealized homogeneous propellants in this environment, infer a transverse pressure gradient will create relative motions among constituents of differing density thereby augmenting mixing and chemical energy deposition i.e. phenomena akin to but different than King's [34] "flame bending" erosive burning model. Moreover, because chemical energy deposition above ~30μm altitude cannot significantly impact propellant regression, this "velocity coupled" chemical energy deposition is expected to possess coupled surface regression and distributed combustion attributes. This complexity, absent from idealized homogeneous propellant grained applicaitons, appears necessary to explain velocity coupled driving [35] i.e. it is "too simple."

Since the velocity field's iso-velocity contours are similar to Fig. 2's iso-temperature contours, non-deterministic vorticity variations in space and time occur at the oxidizer particles' micro-scale i.e. the BS

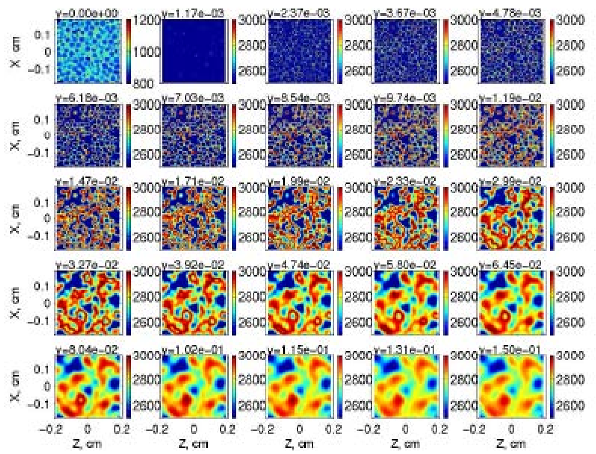

Fig. 2 Temperature Field T(x,z,y_i,t =fixed), K: HT/AP Propellant P86-1320 (*Rocfire* Code simulation courtesy Dr. T.L. Jackson)

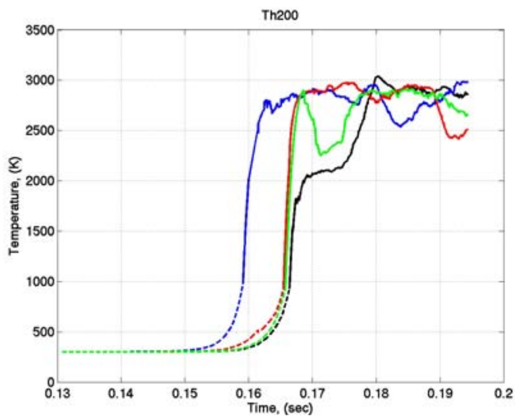

Fig. 3 Ideal Micro-Thermocouple Histories K: HTPB/AP Propellant P86-1320 (*Rocfire* Code simulation courtesy Dr. T.L. Jackson)

‡ The corresponding gas speed tomogram presents panel contours of similar geometry.

efflux is turbulent. Therefore, it creates broadband acoustic energy in isobaric, quiescent environments e.g. listen to a burning strand. In contrast, idealized homogeneous propellants' BS efflux is uniform, irrotational, and *silent* in this environment. Consequently, although pressure oscillations can be absent from stable homogeneous propellant grained applications (the usual assumption), omni-present, low amplitude pressure oscillations are expected in heterogeneous propellant grained applications. Moreover, their attributes can provide mode frequency and acoustic stability margin estimates and qualitative flowfield information [36,37].

Because "cold flows" mimic neither Fig. 2's temperature (and composition) gradients nor its innately non-deterministic in space and time characteristics at the oxidizer particles' micro-scale, they cannot robustly simulate flowfields in heterogeneous propellant grained applications. They are "too simple."

Figure 3's ideal micro-thermocouple measurements differ significantly from idealized homogeneous propellant's monotonic expectation and exhibit large variations among identical micro-thermocouples in the same propellant and environment. Since the paradigm infers this, "would you reject the "bad" data" i.e. that from *obviously* malfunctioning thermocouples?" This example illustrates the paradigm's potential for intellectual corruption. It appears Kubota [38] first connected these impossible (for idealized homogeneous propellant) measurements with heterogeneity.

Idealized homogeneous propellant's ballistic characterizations and internal ballistic theory have been successfully applied to heterogeneous propellant applications in the past [2] and continues to be valuable. However, that age was characterized by (i) developments where failure was not an option, (ii) many new and challenging developments, and (iii) reasonable tolerance for failure (often a necessary learning experience). Therefore, sound engineering practice i.e. empirical knowledge applied by competent and experienced workplace personnel could triumphed over imperfect theory[§]. Unfortunately, our age's continuing attrition of experienced workplace personnel by retirement and death [39,40], relative absence of new programs [39], low (zero?) tolerance for failure [39] during development, and stringent cost requirements imperil solid rocket motor development in workplaces oriented to the past age. Moreover, Ares I [41] suggests heritage solid rocket motor technology per se can be neither low risk nor cost effective. On the other hand, detailed simulation capabilities unavailable in the past age promises to reduce the importance of empiricism with fundamental science. In addition, computer technology promises practical implementations – tomorrow. Consequently, detailed simulation is a promising approach for the challenges of today's and tomorrow's workplace and is widely (and wisely) pursued and implemented.

In summary, ballistic characterization's BCs, governing equations employed to predict application phenomena, and cold flow experiments are not robust for heterogeneous propellant grained applications. Although sound engineering practice accommodated these innate weaknesses and created necessary products in the past's workplace, today's and tomorrows different workplace constraints require different practices to retain vigor and viability.

2 CRITICAL LITERATURE

The INTRODUCTION demonstrates the critical importance of perspective to education, research, and robust engineering applications i.e. if flaws and limitations are unknown "How can danger be assessed?" and "How can research and, or education ameliorate that danger?" Therefore, ballistic characterization's and internal ballistics' challenges are not idealized homogeneous propellant's per se. Rather they are consequences of its dogmatic, wooden headed acceptance without perspective to application realities in the literature. Specific examples and consequences related to heterogeneous propellant grained applications are discussed below to identify this literature and its consequences.

[§] RS Maverick [57] successfully ameliorated excessive omni-present pressure oscillations in stable motors by heterogeneity (and <3% additives to keep burning rate and its sensitivities fixed) variations and adequate motor test data (~30 prototypes).

Price's [42] seminal criticism of idealized homogeneous propellant burning rate models argues

(a) they cannot robustly mimic heterogeneous propellants' local, spatio-temporal variations of regression rate, composition, temperature, topography, etc across the burning surface (BS) at the ox particle micro-scale (see [31-33,38,43,44]'s artifacts) and
(b) spatial mean burning surface (BS) composition changes during transients [45-48] (Steinz and Selzer's BS AP depletions during rapid depressurization extinguishments are compelling evidence) and

the experimental data support Price. Moreover, these experimental results' schlieren images [33], CN spectra [31], micro-thermocouple [32,38,43] and line reversal pyrometry [44] measurements support Figs. 2,3's isobaric deflagration characteristics. Optical temperature and, or specie measurements during and extinguished surface composition measurements after rapid depressurization extinguishments demonstrate significant BS composition and flame temperature variations can occur during transients. Stokes, Hessler, and Caveny's [49] rapid extinguishments demonstrate erosive burning can alter composite propellant's BS's topography and infer (a,b) impacts.

Logical consequences of (a,b) are significant.

(c) Since quasi-steady (QS) processes, where BS composition is constrained to the virgin propellant's steady-state BS composition, cannot robustly mimic (b), conventional QS and QSHOD transient burning rate models [50] are not robust for heterogeneous propellants.
(d) Because Schoyer's [51] analysis of L* instability and (b) (see [52]) infer conventional L* models [53] are not robust, Culick's [54] proof conventional acoustic stability theory includes conventional L* models also infers conventional acoustic stability theory [55] is not robust for heterogeneous propellants.

George and Davidson [56] demonstrate asymptotic turbulent flows are sensitive to their source's spatio-temporal characteristics (large eddy structures *appear* to propagate this information). Therefore, heterogeneity per se is expected to impact the flowfield as RS Maverick's [57] development demonstrates.

In recent and seminal work Massa, Jackson, and Buckmaster [58] prove robustly homogenized heterogeneous propellant requires heterogeneity related source terms in the condensed phase's homogeneous, one-dimensional (HOD) energy equation

$$\partial T/\partial t + r_b \partial T/\partial x = \alpha \partial^2 T/\partial x^2 + S(x,t)/(\rho C) \quad (2)$$

Moreover, *Rocfire* Code results demonstrate $S(x,t)$ can be significant. Furthermore, if Massa, Jackson, and Buckmaster's BS smoothing function is applied to the flowfield's field equations e.g. Eq. (1) – heterogeneity related source terms also appear there. Therefore, idealized homogeneous propellants' smooth, uniform composition BS and deterministic BCs e.g. burning rate, acoustic admittance, etc – require the (a,b) heterogeneity information lost by this assumption be embedded in the condensed phase's and the flowfield's governing equations if predictions for heterogeneous propellant grained applications are to be robust. Consequently, Massa, Jackson, and Buckmaster effectively proves mathematically what the INTRODUCTION infers from philosophical and boundary value problem principles i.e. idealized homogeneous propellant internal ballistics is not robust for applications.

Before proceeding, re-examine Fig. 2, while contemplating the assertions above, and then ask yourself "how could it be otherwise?" Now tabulate operational consequences.

(e) Deterministic flowfield BCs require RANS like field equations that explicitly embed (a,b) information lost. Therefore, Beddini's [59] innovative, pseudo-turbulence BC approach to flowfield prediction with deterministic BCs was prescient although description of and implementation of a rigorous methodology remains.
(f) Flowfield analyses with deterministic BCs and field equations without heterogeneity related source terms cannot be robust for heterogeneous propellant grained applications i.e. (e)'s inverse.

(g) Robust detailed flowfield simulations are precluded for applications by ballistic characterization's absence of explicit non-deterministic information.

Since the BDP genre [11-16] of QS burning rate models' employ spatial averaging, they are limited to deterministic predictions and cannot predict (b) effects. Therefore, they cannot provide robust flowfield BCs for heterogeneous propellant grained applications. Recent developments by Rasmusson and Frederick [14] and Schusser, Culick, and Cohen [15,16] employ the Cohen and Strand model's [13] reactive region component with a sideways sandwich, homogeneous binder and oxidizer model of the condensed phase – see Fig. 4. Although their sideways sandwich geometry enables (b) predictions, their homogeneous components preclude robust transient predictions e.g. Eq. (2). Moreover, their continuous geometry in the regression direction precludes BS AP depletions observed by Steinz and Selzer [45]. Therefore, these models cannot provide robust BCs for flowfield applications and their predictions are not robust for burning rate transients.

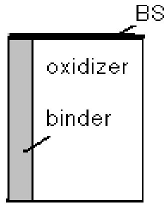

Fig. 4 Sideways Sandwich Model

Although Massa, Jackson, and Buckmaster's QSHOD *Rocburn* Code was mentored by their *Rocfire* Code, its conventional QSHOD inheritance prohibits robust predictions of (b) effects.

McDonald and Menon's [60] DNS simulation of a composite propellant deflagration sourced flowfield with idealized homogeneous propellant BCs but without perspective to either literature or fundamental principles above epitomizes the paradigm. Its technically exact flowfield simulation, complex, reasonable predictions, and the acceptance of its peer reviewers and editor obfuscate its fundamental technical flaw, omitted literature, and deleterious educational impact.

The literature above demonstrates intellectual thought and experimental data from the late 1960's and early 1970's and recent analysis support inferences based on boundary value problem and philosophical principles. Moreover, *Web of Science* citations searches on this literature infers it is seldom employed – particularly as criticism. This absence of perspective in peer and editor reviewed publications (includes texts, monographs, and the AIAA Progress series) supports the Kuhnian paradigm hypothesis and indicates pro-active action is necessary to crush the paradigm and regenerate ballistic characterization and internal ballistics for heterogeneous propellant grained applications in workplace and academy.

3 REGENERATION

INTRODUCTION and CRITICAL LITERATURE demonstrate idealized homogeneous propellant ballistic characterization and internal ballistics are not robust for heterogeneous propellant grained applications and idealized homogeneous propellant is a Kuhnian paradigm that corrupts education, research, and workplace activity. They also demonstrate detailed simulation's capabilities e.g. Figs. 2 and 3 – and robust homogenization's mathematical consequences i.e. heterogeneity related source terms in the condensed phase's and flowfield's governing field equations for deterministic BCs. Finally, Massa, Jackson, and Buckmaster's *Rocfire* Code tutored development of it computationally fast *Rocburn* Code pupil demonstrates detailed simulation's ability to tutor specialized pupils whose characteristics can exceed the tutor's. Moreover, this strategy can obviously be employed to assess and optimize new approaches to ballistic characterization and motor testing. Finally, since detailed causal phenomena are related to detailed effect characterizations by detailed simulation, cause and effect information and detailed simulation provide a complete virtual reality that can be employed to estimate parameters for all components from experimental data. Therefore, detailed simulation enables "bootstrapping." Consequently, detailed simulation's potential rests on four facts.

1. The operational Rocburn Code *realistically* simulates heterogeneous propellant deflagration's *details* (see Fig. 2) albeit imperfectly i.e. acceleration augmentation is not simulated (T.L. Jackson, personal comment, 2006). This suggests BS melt dynamics are necessary.

2. Detailed simulations are savants for their *virtual* realities.
3. Detailed simulations can create specialized, high performance models by tutoring approximate models – note analogy to graduate education.
4. Although detailed simulations are computationally demanding, computational capabilities are adequate for *small* systems.

These capabilities enable solid rocketry to create and operationally implement a higher level of capability in academy and workplace. The objective of this section is to illustrate this approach with specific examples.

3.1 Workplace Diagnostics

3.1.1 Optical Strand Burners

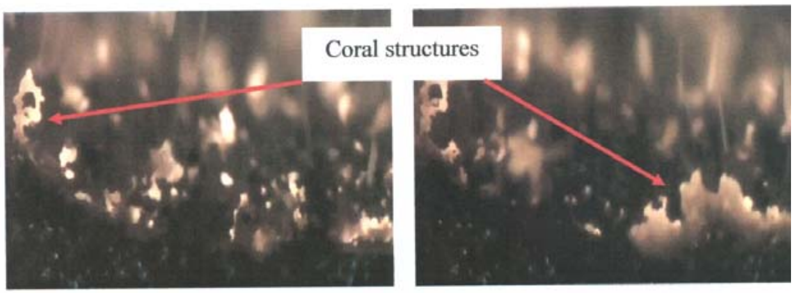

Fig. 5 HTPB/AP/nanoAL propellant deflagration (~72 psi) [61]: Courtesy F. Maggi, Politecnico di Milano.

Idealized homogeneous propellant ballistic characterization and internal ballistics determinism infers all propellants are similar and (a,b) artifacts are insignificant. Therefore, early assessment of this presumptions adequacy is important i.e. if the candidate propellant behaves like idealized homogeneous propellants, exploit this advantage. Commercial availability of high resolution, high framing rate digital image recorders enable concurrent burning rate quantification and qualitative assessment of deflagration phenomena at the strand level with conventional strand burner's** cost effectiveness and through put (strands burned/day). Moreover, because data and images are digital, computer technology enables automatic burning rate reduction and ready information retrieval with flexible search strategies. Therefore, implementation routinely acquires and archives burning rate and deflagration process information for all propellant development and tailoring efforts. Because the potential of computer aided "pattern searches" increases with data base size, this approach's routine acquisition infers *available* knowledge and potential increases with time i.e. a personnel independent institutional memory.

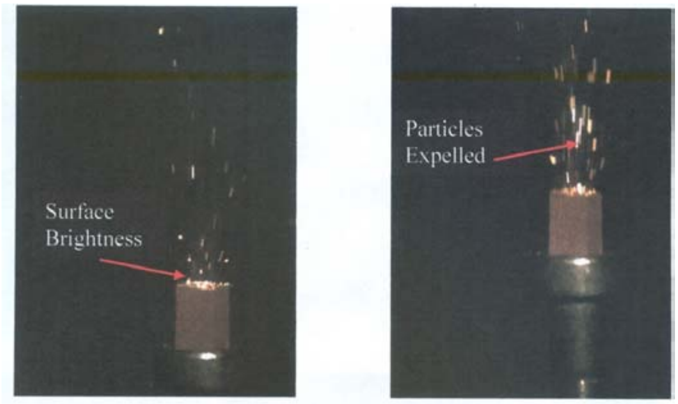

Figure 6. Vibration correlated AL dispersion @ 1atm, ~150g; right acceleration dispersion; left acceleration retention [61]: Courtesy A. Bandera and F. Maggi, Politecnico di Milano.

Figure 5 presents two digital images of propellant deflagration that inform the deflagration process and provide (with the entire image record) an automated mean burning rate estimate. Although conventional aluminized propellant behavior could be expected, Fig. 5 reveals this presumption is not robust because the deflagration process's (a) characteristics are dramatically altered. Ergo, with this propellant

** Because breakwire insertion and connection operations are eliminated, the *operational* cost effectiveness of optical characterization should exceed conventional strand burners'. On the other hand, initial capital costs will be significantly larger.

nanoAL alters (a,b) effects and their attendant impacts on flowfield and condensed phase response to transients environments. Indeed, because the Coral structures protect the BS's rate controlling locations, could they de-sensitize erosive burning? The important generalization is that concurrent burning rate and deflagration process information can sum synergistically to new formulation strategies.

RS Maverick's [57] development demonstrated heterogeneity (with <3% "conventional" additives to achieve iso-burning rate and sensitivities) produced more than an order of magnitude variation in the maximum amplitude of its omni-present pressure oscillations. This brought the motor into compliance with customer requirements. It is inconceivable Fig. 5's mechanistic information and knowledge of (a,b) impacts available from pre-program and during-program formulation studies would not have aided this process.

Figure 6 presents two digital images for a stand of HTPB/AP/AL propellant burning in a vibration environment. They demonstrate AL agglomeration and dispersion can be phase correlated to BS vibration. Moreover, small vibration induced mean burning rate variations have been measured in a very limited mean pressure, frequency, amplitude domain [61]. Since experiments also demonstrate DC acceleration can alter burning rate and AL agglomeration, powered flight's omni-present DC acceleration and vibration environment can create consequences invisible in either static tests e.g. Mars Pathfinder Lander's static test stable, flight test unstable retro-motors – and, or conventional particle collection burners. Therefore, in flight motor behavior can also be informed by adroit strand burner characterizations. Moreover, Bandera, et.al. [62] demonstrates similar digital images can be employed to estimate statistical measures for the dispersed agglomerates (adroit phase correlation should extend their steady state technique to this application).

Available technology can enhance an optical strand burners information production. Since pulse illumination effectively eliminates image blur, dispersed agglomerate size can be estimated if resolution is sufficient. Moreover, schlieren images provide density gradient information (see [32]). Multiple images can be recorded with split frames that provide instantaneous comparisons or as time sequenced images. Furthermore, taut wire BS positioning (Tim Parr, personal conversation, 2003) offers reducing focal volume requirements and enhanced resolution. Finally, taut wire BS positioning offers potential e.g. Fig. 7 – for direct measurement of burning rate and deflagration process initial temperature and formulation sensitivities. Since sensitivities guide propellant formulation, burning rate uncertainty is the primary source of sensitivity uncertainty, and direct measurement of burning rate differences reduces this uncertainty by roughly 40% relative to differences obtained from individual measurements, *if measurement accuracies are identical*, significant uncertainty reductions are possible.

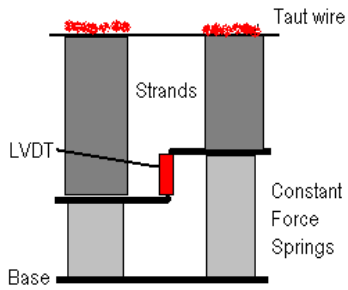

Fig. 7 Taut wire difference measurement schematic

The above argues optical strand burners + digital image recorders enables more information/unit cost *routinely* for basic formulations studies and this information can favorably impact flight applications and characterization of explicit non-deterministic information.

3.1.2 Rotating Valve Burners

Since *Rocfire* Code can relate (a,b)'s area mean manifestations in terms of instantaneous burning rates and flame temperature changes, these idealized homogeneous propellant measures provide indirect measures of (a,b) effects. The rotating valve burners [63] oscillatory pressure environment is currently employed to estimate a propellants' pressure coupled acoustic admittance function by exploiting the burner's large chamber volume characteristics. Therefore, because pressure coupled mass and flame temperature response functions are propellant properties, assuming the rotating valve's area perturbations are invariant i.e. every rotation is identical – enables mass and flame temperature response functions estimated from measurements at two different chamber volumes as

$$\Theta_f = \left[-\frac{\omega_c \cdot \left[(2\cdot\varepsilon_1 - 2\cdot\varepsilon_2)\cdot\tau_{ch2} + \tau_{ch1}\cdot(2\cdot\varepsilon_1 - 2\cdot\varepsilon_2) \right] + 2i\cdot\left(\omega_c^{2}\cdot\tau_{ch1}\cdot\tau_{ch2} - 1\right)\cdot(\varepsilon_1 - \varepsilon_2)}{\omega_c\cdot\left[\varepsilon_1\cdot\varepsilon_2\cdot(\tau_{ch1} - \tau_{ch2})\right]} \right]\cdot\Psi + \frac{\gamma + 2\cdot i\cdot\omega_c\cdot(\tau_{ch1} + \tau_{ch2}) - 2\cdot\tau_{ch1}\cdot\tau_{ch2}\cdot\omega_c^{2} + 1}{\gamma}$$

$$R = \frac{\omega_c\cdot\left[(\varepsilon_1 - 2\cdot\varepsilon_2)\cdot\tau_{ch2} - \tau_{ch1}\cdot(\varepsilon_2 - 2\cdot\varepsilon_1) \right] + i\cdot\left(2\cdot\omega_c^{2}\cdot\tau_{ch1}\cdot\tau_{ch2} - 1\right)\cdot(\varepsilon_1 - \varepsilon_2)}{\omega_c\cdot\left[\varepsilon_1\cdot\varepsilon_2\cdot(\tau_{ch1} - \tau_{ch2})\right]}\cdot\Psi - \frac{1 + 2\cdot i\cdot\omega_c\cdot(\tau_{ch1} + \tau_{ch2}) - 4\cdot\omega_c^{2}\cdot\tau_{ch1}\cdot\tau_{ch2} - \gamma}{2\cdot\gamma} \tag{3}$$

Therefore, in principle, a rotating valve burner with a multi-frequency rotating valve could estimate $R(\omega_c : \bar{p}, T_o, formulation)$, $\Theta_f(\omega_c : \bar{p}, T_o, formulation)$, and $\bar{r}_b(\bar{p}, T_o)$ in a single test from pressure measurements and burner geometry alone. Moreover, with ultrasound instrumentation a direct estimate of burning rate and pressure coupled mass response function R_{US} are available. Since the pressure coupled mass response function is a property, R_{US} estimates must be independent of τ_{ch} when mean pressure is. Ergo, ultrasound instrumentation provides an indirect assessment of the rotating valve's forcing function invariance.

Because R_{US} depends on the condensed phase's temperature field and the BS's topography and local burning rate varies across the BS in space and time, R, R_{US} differences offer indirect information that pertains to (a,b). In the past, the efficacy of [61]'s bulk mode analysis was assumed. However, a *Rocfire* Code based detailed simulation now enables a virtual assessment of Eq. (3)'s efficacy. Moreover, a virtual assessment of the ultrasound burning rate measurements sensitivity to (a,b) effects may also be possible and would indirectly relate R, R_{US} differences with (a,b). Therefore, a number of indirect sources of (a,b) information exist that detailed simulation can assess (and optimize if viable).

Micci [64] demonstrated an MHD burner based on a uniform magnetic field, two electrode MHD flowmeter for direct pressure coupled acoustic admittance measurements. A characteristic of this burner is its extremely noisy MHD flowmeter measurement. Moreover, because the MHD model assumes the flowfield is axisymmetric but (a) invalidates this assumption, this noise is expected and related to (a,b). Therefore, (a,b) estimates *in statistical form* may be possible. Since multiple electrodes and uniform magnetic field enable velocity profile estimates in an axisymmetric flow, velocity profile measurements in asymmetric flows present a fundamental challenge.

Since the magnetic field is the free variable, are multiple electrodes and an appropriate non-uniform magnetic field adequate? In short, can multiple electrodes and a magnetic field that rotates during the measurements provide asymmetric velocity profile estimates? Assuming this is possible, note magnetic field rotations correlated with the rotating valve's forcing could provide statistical measures of the instantaneous velocity profile. Recall that mass response is a property and phase correlation would provide repeated velocity profile measures throughout the forced pressure oscillation cycle. Therefore, *Rocfire* Code based simulation's create opportunity.

3.1.3 Motor Testing

Instrumentation for a conventional static motor test typically consists of thrust and head end pressure measurements. Hessler [36] demonstrates modal frequency, modal stability margin, and flow structure estimates can be obtained from head end pressure measurements if the oscillation pressure portion has adequate s/n[††]. Therefore, the applications omni-present pressure oscillations provide a passive and essentially free information source. Hedge and Strahle [37] demonstration that the head

[††] Culick and Seywert [65] demonstrate pulsing is more accurate for non-optimal fitting (optimal fitting impacts not examined).

end's omni-present pressure oscillations are rich in acoustic information and the aft end's are rich in fluid dynamic information support the efficacy of Hessler's approach and infer additional information is available from the aft end's omni-present pressure oscillations. Consequently, Rocfire Code based detailed simulations' omni-present pressure oscillations could assess the fidelity of these estimates. Moreover, because these measures are related to flowfield's BCs by the simulation, these measures could indirectly calibrate these BCs.

The objective of the aforementioned examples is to suggest the feasibility of a new approach based on *Rocfire* Code based simulations. However, challenges arise in implementations. For example, would RANS like models with deterministic BCs that can be quantified and innately statistical information that "characterizes" the BS's non-deterministic efflux be superior? Moreover, what is the rigorous form of these RANS like equations? Therefore, transcending the idealized homogeneous propellant paradigm opens new vistas to fundamental issues that are significant in both academy and workplace.

3.2 Deflagration Models

Fig. 8 Oxidizer Particle Evolution Diagram

As noted above, the *Rocburn* Code (*Rocfire* Code's pupil) is not robust because its conventional QSHOD implementation precludes (b) effects. However, Schusser, Culick, and Cohen embedded (b), albeit imperfectly, with a sideways sandwich condensed phase model. Therefore, could this strategy i.e. segregating oxidizer and binder heat feed backs and applying them separately to oxidizer and binder components – ameliorate this defect (or lead to amelioration)? Moreover, embedding Eq. (2) in the condensed phase energy equations of Schusser, Culick, and Cohen's small perturbation model would enhance its fidelity to heterogeneous propellant realities. Furthermore, substituting *Rocfire* Code reactive region information for the Cohen Strand model's would upgrade that component and implicitly provide non-deterministic BS efflux information. This strategy is particularly attractive because a closed form solution may be available with the source term $S(x)$ [‡‡] as an unknown parameter. Consequently, experimental $R(\omega_c : \bar{p}, T_o, formulation), \Theta_f(\omega_c : \bar{p}, T_o, formulation)$, and $\bar{r}_b(\bar{p}, T_o)$ data would now offer an implicit $S(x)$ estimate and calibrate this model for a specific propellant.

Non-deterministic information can be embedded in BDP genre models by replacing their spatial averaging i.e. averaging over oxidizer particle micro-states on the BS. Figure 8 presents an evolution diagram for a BDP model's oxidizer particle. It is effectively born when it reaches the BS, evolves through its life there, and dies by either burnup or dispersion. For a propellant with mono-disperse oxidizer, this life history is, to an approximation, identical for all particles. Therefore, application of the BDP model to an oxidizer, binder pair i.e. Beckstead [66] – defines this history for isobaric deflagration. Consequently, this histories response to small amplitude pressure oscillations will depend solely on the oxidizer's particle's birth relative to the pressure oscillations "clock." Hence, a sequence of computations with this measure of "birth time" as a parameter will define the response of all BS oxidizer states and the ensemble's response by integration. Since Beckstead's results reveal factor of 3 variations in instantaneous burning rate and product's o/f ratio during the oxidizer particle, binder pair's life, interesting (a,b) predictions are anticipated.

[‡‡] Since this strategy can be robust only for small perturbations, the time dependence required for non-linear processes is dropped.

3.3 Summary

Windowed strand burners and digital image recording offers concurrent burning rate and deflagration process characterization at conventional stand burner cost/strand and time/strand. Moreover, information/unit cost can be enhanced with technical development. Rotating valve burners should provide concurrent pressure coupled mass and flame temperature response function estimates and the MHD burner may have potential for statistical velocity profile measurements. High s/n measurements of omni-pressure pressure oscillations at head and aft ends during motor testing offer estimates of acoustic mode frequencies, stability margins, and flowfield related information. Coupling this information with appropriate detailed simulations offers indirect characterization of (a,b) effects necessary for robust application predictions. Since the exact path to this goal is not yet clear (and no single path may be sufficient), continuing development of detailed simulation, diagnostics, synergistic combinations, and effort are necessary.

4 CONCLUSIONS

Idealized homogeneous propellant ballistic characterization and internal ballistics are not robust for heterogeneous propellant grained motors that dominate applications. Moreover, idealized homogeneous propellant is a Kuhnian paradigm that inhibits research, corrupts education, and penalizes application developments in the work place. Although history demonstrates its past usefulness and it retains value, our age's ongoing attrition of experienced personnel, scarcity of new developments, intolerance of failure, and stringent cost demands' have created new workplace parameters that reduce the paradigm's value in the workplace and increase its risks. Since adroit application of detailed simulation can ameliorate the paradigm's challenges in workplace and academy, why not begin to work smarter? This paper sketches some approaches for workplace and academy. Because the paradigm corrupts solid rocket education, minimizing harm is critical and this is easily accomplished i.e. *demand* perspective to critical references in peer and editor reviewed publications. Pro-active progress can be achieved by focusing on these challenges – as this session does.

NOMENCLATURE

c	secific heat	ε	non-dimensional pressure oscillation,
p	pressure	γ	specific heat ratio
r_b	burning rate	ρ	density
R	pressure coupled mass response function	Θ_f	flame temperature response function
t	time	$\vec{\tau}$	shear stress tensor
T	temperature	τ_{ch}	chamber residence time
$\vec{u}$	velocity vector	ω_c	circular frequency
x,y,z	spatial coordinates	Ψ	rotating valve area function
α	thermal diffusivity	$(\ )_{1,2}$	subscripts denote states 1 and 2

ABBREVIATIONS

BC	boundary condition	BS	burning surface	AP	ammonium perchlorate	AL	aluminum

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