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Introduction: Perspectives on Detonation-Based Propulsion

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DETONATION, a shock-induced combustion process in which the heat release makes a strong contribution to the support of the lead shock, is one of the most rapid chemical energy release processes in nature. For self-sustained detonations propagating in gases initially at atmospheric pressure and temperature, energy release rates approaching 10^{10} W/m^2 are not uncommon, and propagation velocities on the order of 10^3 m/s can be achieved. These rapid speeds are attained because the major mechanism of energy transport in a detonation is acoustic; other slower modes exist as well. In contrast, common deflagration flames, such as might be present in candles or furnaces, have speeds which are mainly dictated by the slower diffusion mechanism, yielding a far lesser energy flux for the same mixture.

Although the design of practical combustion-based engineering devices is dominated by the easier-tamed deflagration, the dramatic energy release rates which can be achieved in the same mixtures in detonation conditions have for decades enticed engineers to seek ways to harness such waves. It is fair to say that the bulk of human efforts over the centuries regarding detonations has been expended in the allied field of reactive solids, with application mainly to weapons, mining, and earth moving. However, since the dawn of the era of high-speed propulsion in the 1940s, an uneven, but ever-present effort has been underway to use detonation in practical propulsion devices. In early years, many of these devices were conceptual only; indeed, today many of them remain in this state. However, over the past two decades, some devices have moved from the drawing board, into the laboratory, and into various stages of the development process. Most notable among these are ram accelerators and pulse detonation engines (PDEs).

The topic of such detonation-based propulsion systems spans several disciplines in basic and applied sciences, in particular, combustion and detonation physics and chemistry, heat and mass transfer, material science, aerospace and mechanical engineering, as well as the allied fields of applied mathematics and scientific computing. Research prototypes of pulse and continuous detonation engines are being developed worldwide with possible applications in a variety of propulsion units, from microthrusters for orbital orientation to afterburners in jet engines. Despite these efforts involving state-of-the-art knowledge and technologies, it is becoming clear that the nonconventional performance goals imply the requirement of novel intelligent approaches and technologies embedded in this type of propulsion system. Standard performance measurement techniques used in conventional propulsion units are not appropriate for highly transient and harsh detonation processes. Although theoretically detonation propulsion is of enormous practical significance and potential, there are still many important issues that arise when examining the test results of existing research prototypes. For example: Are detonation engines truly a practical reality? Can detonation engines significantly improve the propulsive performance of air-breathing or rocket engines? What is the major advantage of detonation propulsion, efficiency or simplicity and ease of scalability? What is the optimal design for such engines? These and many other questions are still waiting to be answered.

To use oblique or propagating detonations for propulsion and realize the corresponding advantages, a number of challenging fundamental and engineering problems have yet to be solved. These problems deal with low-cost achievement and control of detonations in a propulsion device. To ensure rapid development of a detonation wave, one needs to apply 1) an efficient liquid or gaseous fuel injection and air-supply system to provide fast and nearly homogeneous mixing of the components in the detonation chamber; 2) a low energy source for detonation initiation to provide fast and reliable detonation onset; 3) a cooling technique for rapid, preferably recuperative, heat removal from the walls of a detonation chamber to ensure stable operation and avoid premature ignition of a fuel–air mixture leading to detonation failure; 4) a geometry of the combustion chamber to promote detonation initiation and survival at the lowest possible pressure loss; and 5) a control methodology that allows for adaptive, active control of the operation process to ensure optimal performance at variable flight conditions, while maintaining a margin of stability. In addition to the fundamental issues concerning the processes in the detonation chamber, there are other issues such as efficient integration of the chamber with inlets and nozzles to provide high performance. Among the most challenging engineering issues is the durability of the propulsion system. As the structural components of a PDE are subject to repeated high-frequency shock-loading and thermal deformations, considerable wear and tear can be expected within a relatively short period of operation. The other problems relevant to PDEs are noise and vibration.

That said, periodically, it is useful for the propulsion community to take stock of the present state of the art, and the editorial leadership of the *Journal of Propulsion and Power* came to the conclusion in the fall of 2004 that it would be useful to publish a compendium of articles in a special section devoted to "Detonations in Propulsion." The goal of the section is to assemble contributions from a worldwide cohort of active researchers in detonation science and propulsion to share their expertise in their area of specialty as it relates to the topic of the special section. A decision was made early on to include a mix of experimental and theoretical works, as well as a mix of studies of the fundamental science of detonation and more practical applications. Following careful consideration which balanced many competing concerns, the editors were fortunate to assemble a distinguished team of 15 contributors who represent many of the diverse communities and who have a common interest in detonation science and propulsion; through their efforts, 11 papers appear. It is, of course, unfortunate that space limitations and previous commitments of some authors combined to restrict the topics which could be covered in this special issue. The issue has been divided into three sections: 1) Propulsion Applications of Detonation, 2) Gas-Phase Detonation Fundamentals, and 3) Heterogeneous Detonation Fundamentals. Next, we summarize the papers which appear.

The section of propulsion applications commences with a contribution by C. M. Brophy and R. K. Hanson, who describe diagnostic techniques for fuel distribution measurements which have relevance in ascertaining performance parameters for PDEs. This is followed by the paper of S. M. Frolov who describes a demonstrator of the liquid-fueled, air-breathing PDE with a design combining several new principles and technologies. Next, A. J. Higgins reviews the rich literature describing ram accelerators and summarizes important future possibilities for research and development of this device. Turning to modeling studies of practical devices, F. H. Ma, J.-Y. Choi, and V. Yang give a detailed discussion of simple and detailed models of practical PDEs along with original calculations. Last, F. A. Bykovskii, S. A. Zhdan, and E. F. Vedernikov describe the application of continuous spinning detonations in rocket motors and ramjet combustors.

The next section, gas-phase detonation fundamentals, is led by a paper by J. M. Powers reviewing multiscale modeling techniques as applied to detonation. This is followed by the discussion of D. S. Stewart and A. R. Kasimov as to how the rich literature in the allied field of detonation stability may have application in detonation-