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Introduction to “To the Question of Energy Use of Detonation Combustion” by Ya. B. Zel’dovich

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Ya. B. Zel’dovich (1914–1987) made numerous contributions[1] to the theory of detonation, beginning with his very well-known and widely translated article[2] on detonation structure that first introduced the standard Zel’dovich-von Neumann-Döring (ZND) model of shock-induced combustion. Even at that early stage of detonation research, Zel’dovich was also considering the application of detonations to propulsion and power engineering. He published these ideas in another paper[3] that has been virtually unknown in the West and has apparently remained untranslated until now. We are indebted to Sergey Frolov of the N. N. Semenov Institute of Chemical Physics for first bringing this article to our attention. We believe that the focus of this paper, which is the application of detonation waves to power generation and propulsion, is very relevant to the current activity on pulse detonation engines. In particular, Zel’dovich was apparently the first researcher to consider the questions of the relative efficiency of various combustion modes, the role of entropy production in jet propulsion, and the distinction between unsteady and steady modes of detonation in power engineering and propulsion applications. Even 60 years later, we believe that his results are relevant and can be of value in modern discussions on thermodynamic cycle analysis of detonation waves for propulsion.[4] For these reasons, we have arranged for the paper to be translated and suggested that it be published by the *Journal of Propulsion and Power*.

The paper is clearly written, and there is no need for extensive commentary, so we only sketch some connections with contemporary work. Sections 1–3 are concerned with the correct computation of the energy budget in an unsteady cyclic process and the thermodynamic efficiency. Zel’dovich recognizes that one has to account for the work necessary to sustain the detonation wave (through a piston, for example) when calculating the work that can be done by the products. This idea was also independently developed by Jacobs[5] and later Fickett and Davis,[6] although they were concerned primarily with high explosives. More recently, we have revisited this idea[7] and carried out computations for mixtures and conditions relevant to pulse-detonation-engine operation. To our knowledge, Zel’dovich was the first researcher to conduct a thermodynamic analysis of a cycle involving a detonation. His conclusion that the efficiency of this cycle is always slightly larger than that of a cycle using constant-volume combustion (Humphrey cycle) has been confirmed many times since.[8–10] Zel’dovich’s formal results for the thermal efficiency are identical to the results of recent studies.[7,9] The specific numerical values given in the main body are, as Zel’dovich recognized, rough estimates and deviate substantially from detailed computations based on realistic thermodynamic properties. Despite the incorrect values for thermodynamic states, his final results regarding the differences in cycle efficiency are quantitatively correct. Repeating[7] his computations with realistic thermodynamic properties gives a value of $\eta'_B = 0.26$ and $\eta_D = 0.30$ for the C_2H_4-air example discussed in Sec. 3, which yields the same 13% increase in the efficiency of the detonation cycle over constant volume as Zel’dovich estimated. Clearly, Zel’dovich knew that his results could be open to criticism because of the roughness of his estimates, and he addressed this with his late addition of the final section “Note Added in Proof.” Those results are within 1% of values computed with modern values of thermodynamic properties and numerical solution of the equilibrium states.

In Sec. 4, Zel’dovich considered using a detonation wave in a steady-flow airbreathing engine. Looking at a detonation wave as a shock wave followed by a reaction zone, he qualitatively argued that this process generates more entropy than a deflagration and showed that using a steady detonation instead of a deflagration resulted in a lower thrust, in agreement with many later studies.[11–14] He gives a numeric example for a very simplified situation [ramjet traveling at the Chapman–Jouguet (CJ) velocity], for which the thrust of a detonation-based ramjet is a factor of two lower than that of an ideal isentropic inlet with constant-pressure combustion. As in the cycle analysis, his numerical values of the exhaust velocity are only rough estimates, and results using realistic thermochemistry yield values of Δu that are approximately a factor of two higher than Zel’dovich estimated. Reevaluation using realistic thermodynamic properties gives a value corresponding to Fig. 4 of $\Delta u = 438$ m/s, and that corresponding to Fig. 5 is $\Delta u = 950$ m/s. The ratio of the thrust for the constant-pressure case to the detonation case is 2.2, exactly the same as Zel’dovich found so that his final conclusions are not only qualitatively but also quantitatively correct.

Although Zel’dovich correctly concludes that the performance of steady detonation-based engines is inferior because of the irreversible entropy generation in the shock wave, he makes no attempt to reconcile this with the minimum entropy character of the CJ state that he discussed in Sec. 3 and subsequent authors have taken as the formal basis for the superiority of detonation-based power generation or propulsion. Recently, we have reexamined[7] this issue and shown that the difference between the constraints in upstream states for steady (fixed stagnation conditions) and unsteady applications (fixed static states) is key in resolving this apparent contradiction.

The notation and units used by Zel’dovich are reasonably clear. The energy units are given in cal/mol for heat of combustion and enthalpy; the heat capacity units are cal/mol·K; the pressure units are kgf/cm^2, $\text{kgf/cm}^2 = 0.980665$ bar. In accord with the practice in chemical physics literature of that era, an explicit conversion factor between thermal and mechanical units is not used. Most symbols are defined in the text and have the usual modern meanings; the symbol J is used to denote the heat content, which present-day readers will recognize as the specific enthalpy. Although the reaction formula given in Sec. 4 does not include nitrogen, the numerical values and setting of the problem make it clear that Zel’dovich is considering the explosive mixture to be stoichiometric C_2H_4 air, and his initial conditions are 1 bar and 300 K. The figures have been redrawn and translated for clarity but are strictly faithful to the originals with the exception of the addition of axes labels to Fig. 3.

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