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Impact of Dissociation and Sensible Heat Release on Pulse Detonation and Gas Turbine Engine Performance

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July 2001

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IMPACT OF DISSOCIATION AND SENSIBLE HEAT RELEASE ON PULSE DETONATION AND GAS TURBINE ENGINE PERFORMANCE

ISABE 2001–1212

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Abstract

A thermodynamic cycle analysis of the effect of sensible heat release on the relative performance of pulse detonation and gas turbine engines is presented. Dissociation losses in the PDE are found to cause a substantial decrease in engine performance parameters.

Introduction

The feasibility and demonstration of pulse detonation engines (PDE) have been investigated for over 50 years. Numerous publications have appeared describing the potential for this type of propulsion device. Kailasanath[1] has published a recent comprehensive review that examines the application of detonation waves to propulsion devices. Reference 1, which includes 100 citations, provides an excellent review of the analytical and experimental progress in the application of detonative phenomena to propulsion systems. Variations in performance estimates were systematically examined and possible reasons for the observed variations were presented.

A common approach for establishing PDE thermodynamic cycle performance has been to assume that a constant volume cycle (i.e., the Humphrey cycle) is a reasonable simulation.[1,2] However, in a recently completed NASA-sponsored effort, Heiser and Pratt[3] employed closed form, algebraic solutions for the leading edge normal shock wave (Chapman-Jouguet) Mach number (M_{CJ}) and entropy rise of the detonation wave. This enabled them to perform a PDE cycle analysis, and make a direct comparison with the Humphrey cycle and the Brayton cycle.

The cycle analysis of Heiser and Pratt employs a generic non-dimensional heat release parameter, $\tilde{q}$, which is a function of the equivalence ratio and lower heating value of the fuel-air mixture. This heat release parameter was used to evaluate the relative performance of the PDE, Humphrey and Brayton cycles.[3]

Comparison of the cycle analysis predictions with engine data requires a specific evaluation of the sensible heat release, rather than the nominal values used in reference 3. Changes in gas properties and compositions need to be considered. This paper examines the effect of sensible heat release on the cycle performance. The results are examined in light of the high temperatures occurring during the detonation process.

Analysis and Procedure

Current Air-Breathing Cycle Analysis

Since this paper builds on the analysis of reference 3, it is appropriate to describe those previous results. The amount of heat supplied, or heat added, during a cycle was defined, to a first approximation, as the product of the mass fuel-air ratio and the lower heating value of the fuel. This quantity was then normalized by $c_P T_{o,}$ to give the non-dimensional heat release parameter,

$$\tilde{q} = f\, h_{LV} / c_p T_0 \, .$$

Typical values of $\tilde{q}$ range from 5 to 10, and were used in reference 3 to evaluate the relative cycle performance parameters. Equivalent $\tilde{q}$ values were used for the Brayton, Humphrey, and PDE cycles, assuming that all of the ideal engines operated with the same initial conditions and the same amount of heat added during their cycles. A result of their analysis is shown on a temperature-entropy diagram in figure 1. This result assumed isentropic inlet compression and nozzle expansion.

The corresponding thermal efficiency curves are shown in figure 2. For the selected parameters of figure 2, the Humphrey cycle closely simulates the PDE cycle. However, it was shown in reference 3, that with non-isentropic component efficiencies, the Humphrey cycle remains high, whereas, the PDE cycle falls off significantly. The consequences of these changes is that at values of T_3/T_0 greater than 3, the Brayton cycle turns out to be a better simulation of the PDE than the Humphrey cycle.

The corresponding specific thrust (i.e., thrust per unit mass flow of air) is shown in figure 3 for $\tilde{q}$'s of 5 and 10 and vehicle speed of zero.

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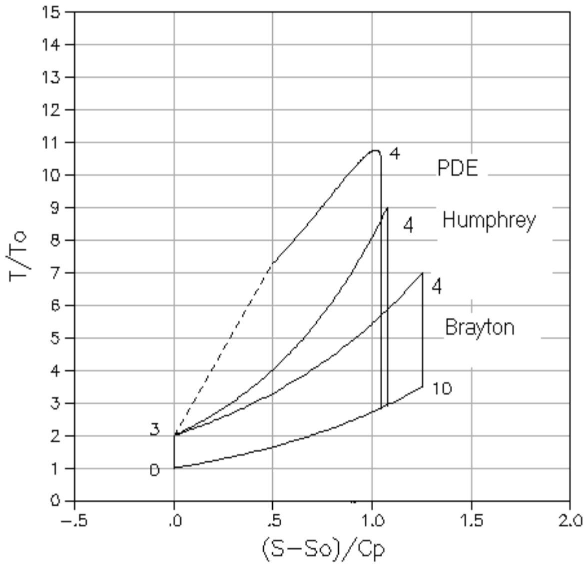

Figure 1. Temperature-entropy diagram for the ideal PDE, Humphrey and Brayton cycles, $T_3/T_o = 2$, $\tilde{q} = 5$, $\gamma = 1.4$, from reference 3.

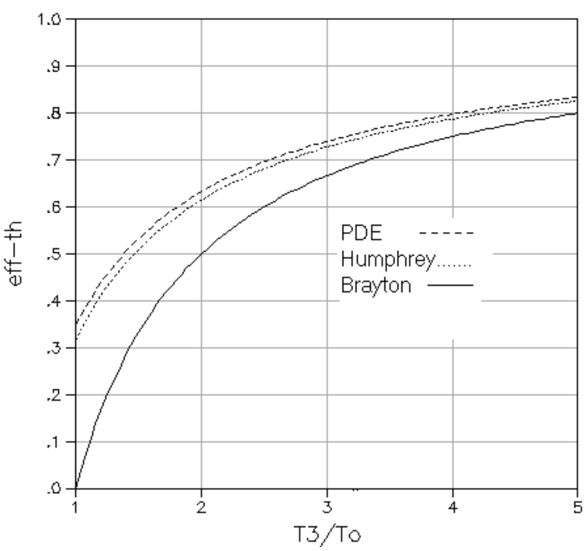

Figure 2. Thermal efficiency for $\tilde{q} = 5$, from reference 3.

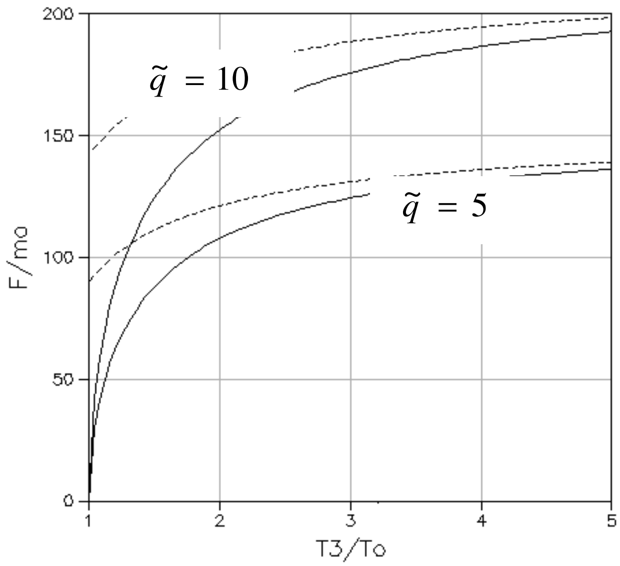

Figure 3. Specific thrust (lbf-s/lbm) of PDE and Brayton cycles for $V_o = 0$, $\gamma = 1.4$, from reference 3.

Values of ψ (equal to T_3/T_0) correspond to isentropic mechanical compression ratios represented by $\psi^{\gamma/(\gamma-1)}$, or to ram compression equal to: $M_0 = \sqrt{2(\psi - 1)/(\gamma - 1)}$ (see reference 3). With the background of the results of reference 3 presented above, we are now prepared to address the issues of the present paper, namely, the determination of the non-dimensional heat release, $\tilde{q}$, for specific fuels and engine operating conditions. In addition, we will examine the effect of dissociation on the sensible heat release available for thrust.

Heat Release Parameter

The detonation properties can be obtained using the method of Zeleznik and Gordon[4] and the *CEA* code of McBride and Gordon.[5,6] Pratt[7] has developed a useful application code, *EQL*, based on references 4 to 6, which is used in this study to determine the sensible heat release, h_{PR}. The non-dimensional heat release, $\tilde{q}$, is determined from the relationship:

$$\tilde{q} = f\, h_{PR}/c_p T_0 \qquad (1)$$

h_{PR} in equation (1) is determined from an energy balance for the overall reaction process, where the relationship between the enthalpies of formation of each species and the heating value of the fuel are determined from an energy balance:[8]

$$h_{PR} = (H_{reactants})_{298} - (H_{products})_{298}$$

where; H_r or H_p are defined as the summation of the products of all species and their standard heats of formation, i.e., $\sum_{i+1}^{NS} n\Delta h^0_{f\,298}$.

EQL may also be used to compute the Chapman-Jouget (*CJ*) parameters for a given fuel-air mixture at the inlet exit conditions (point 3 in figure 1); and $\tilde{q}$ may be determined from equation (2) for a given ψ:[3,9,10]

$$M_{CJ}^2 = (\gamma + 1)\frac{\tilde{q}}{\psi} + 1 + \sqrt{[(\gamma + 1)\frac{\tilde{q}}{\psi} + 1]^2 - 1} \qquad (2)$$

The resulting $\tilde{q}$ from equation (1) was used to perform cycle calculations for the PDE. In the case of the Brayton cycle, the sensible heat calculated from *EQL* was also used. Dissociation losses in the Brayton cycle may be recovered in the recombination process during turbine/nozzle expansion. In a similar fashion, some PDE recombination may occur during nozzle expansion. However, since practical PDE nozzles are not well defined, recombination in both cycles is not considered in this paper.

Results

Sensible Heat Release

Calculations, using *EQL,* were initially performed for a stoichiometric mixture of propane and air at standard pressure and temperature and $\psi = 1$. The resulting values for the detonation process were:

$M_{CJ} = 5.32$, $T_4/T_0 = 9.43$, $P_4/P_0 = 17.6$, $c_p = .358$ BTU/lbm °R, $\gamma = 1.25$ and $h_{PR} = 16{,}508$ BTU/lbm fuel.

$\tilde{q}$ was then calculated using equation (1), yielding a value of 5.5.

In a corresponding fashion, an h_{PR} value of 18,572 BTU/lbm fuel and a $\tilde{q}$ value of 6.3 were determined for the normal (Brayton) combustion process. The sensible heat release associated with the detonation is seen to be 11 percent lower than that for the normal deflagration process. The temperature reached during deflagration was 4080 R whereas with detonation it was 5056 R. Inspection of the chemical species following reaction shows that the amount of intermediate products were substantially greater for the detonation process. The amount of CO, NO, OH, and H was 2 to 4 times higher than the deflagration process; and the HO_2 was 12 times higher. With the higher amount of intermediate species, it is reasonable to attribute the lower h_{PR} to the dissociation losses occurring during the detonation process.

Cycle Calculations

For comparative purposes the cycle code developed in reference 3 is used to evaluate the performance of the relative cycles. It is noted that the cycle analysis is based on constant gas properties and an ideal equation of state. It assumes that all particles of fuel and air undergo the identical detonation process. The results are only a measure of the maximum ideal performance available. The cycle analysis cannot generate information relative to practical aspects of a propulsion system, such as weights of the system, number of moving parts (simplicity) and costs. Those issues must rely on tests of specific components.

Thermal Efficiency

The thermal efficiency and specific thrust are shown in figure 4a and 4b for the Brayton and PDE cycles. The parameters used for these calculations were those corresponding to the *EQL* results discussed above in the Sensible Heat Release section. For a PDE using propane/air with an equivalence ratio $\varphi = 1$ ($\varphi = [\text{fuel/air}]_{actual}$ / $[\text{fuel/air}]_{stoichiometric}$), and a temperature ratio ψ of 1, $\gamma = 1.25$, $\tilde{q} = 5.5$, $c_p = .358$ BTU/lbm °R. For the Brayton cycle, the $\tilde{q} = 6.3$ at $\varphi = 1$.

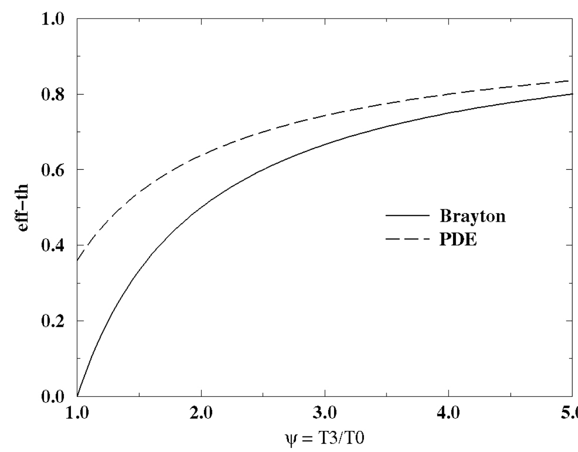

Figure 4a. Thermal efficiency, [(heat supplied-heat rejected)/ heat supplied], $V_0 = 0$, $\gamma = 1.25$, stoichiometric propane-air.

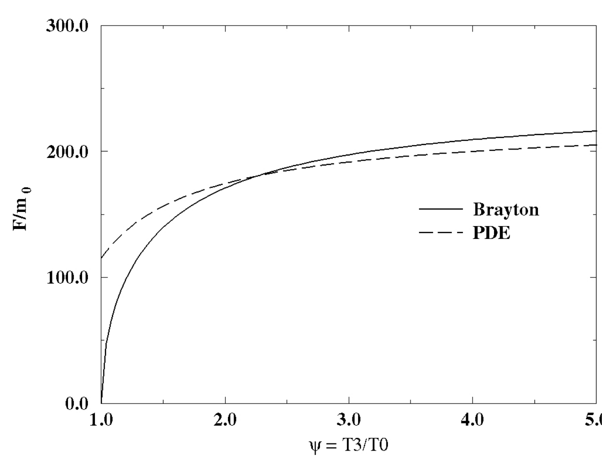

Figure 4b. Specific thrust (lbf-s/lbm), $V_0 = 0$, $\gamma = 1.25$, stoichiometric propane-air.

The thermal efficiency for the PDE cycle is seen to be equal to that in figure 2. This correspondence is due to the slightly higher value of $\tilde{q}$ used with propane-air, a higher γ value, a higher c_p and a higher reference temperature than those used in reference 3. The specific thrust is shown in the following figure.

The significant feature of figure 4b, as compared to figure 3, is that the PDE thrust/air flow crosses over the Brayton cycle curve at temperature ratios slightly above 2. This result is due to the lower sensible heat release available in the PDE cycle.

Maximum heat release

EQL was further run to determine the propane/air ratio for the largest sensible heat release. The value was an equivalence ratio of 1.1, with a sensible heat release, $\tilde{q}$, of 5.63 for the detonation process and 6.38 for the deflagration process. Use of these values yielded a small increase in the level of the specific thrust curve, and the crossover point between the PDE and Brayton curves shifted a small amount to a higher temperature ratio, occurring at a ψ value of 2.3. This result is shown in figure 5.

Fuel Type

Various hydrocarbon mixtures were investigated to ascertain the sensible heat release in a detonation condition. Virtually all of the C_xH_y combinations have $\tilde{q}$ values ranging from 6.3 (Acetylene, C_2H_2) to 5.3 (methane, CH_4). Using a $\tilde{q}$ of 6.3 for the PDE and the corresponding deflagration $\tilde{q}$ value of 7.37, gives the result shown in figure 6.

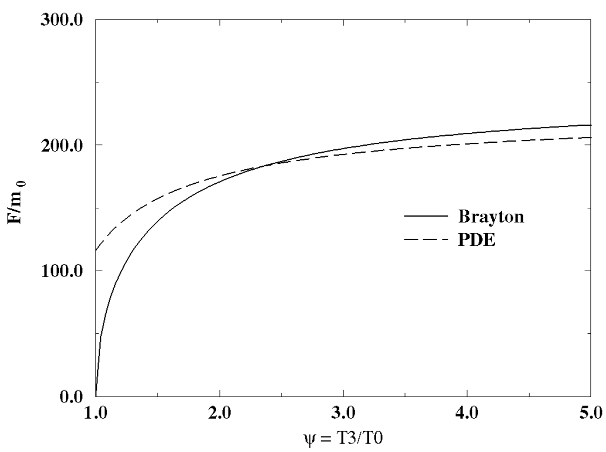

Figure 5. Effect of maximum heat release on specific thrust (lbf-s/lbm), $V_0 = 0$, $\gamma = 1.25$, $\varphi = 1.1$, propane/air.

The overall levels of specific thrust for both cycles are higher than the previous results with propane. However, the point at which the thrust of the PDE becomes equal to the Brayton value (crossover point) is seen to remain at a value of 2.25, as observed with the propane result shown in figure 4.

Calculations were also carried out using stoichiometric hydrogen/air. The $\tilde{q}$ values are 5.5 for detonation, and 6.8 for deflagration. The results are plotted in figure 7. The crossover point on specific thrust occurs at about 2.

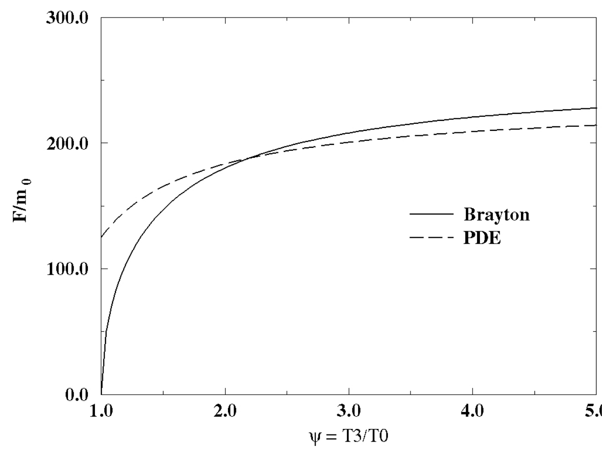

Figure 6. Specific thrust (lbf-s/lbm), stoichiometric acetylene/air, $V_0 = 0$, $\gamma = 1.26$.

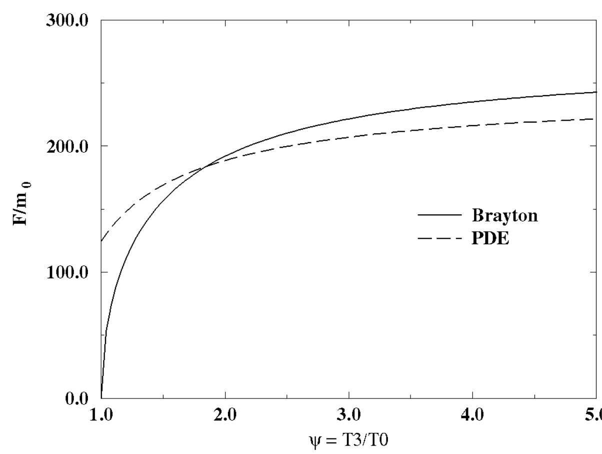

Figure 7. Specific thrust (lbf- s/lbm), stoichiometric hydrogen/air, $V_0 = 0$, $\gamma = 1.24$.

Specific Fuel Consumption

The specific fuel consumption was determined from the mass flow rate of fuel per unit of thrust:

$$\mathrm{SFC} = \frac{\dot{m}_f}{F} = \frac{f}{F/\dot{m}_0}. \qquad (3)$$

Calculations for stoichiometric propane/air are shown in figure 8.

It is noted that the ideal PDE cycle has lower fuel requirement per pound of thrust from static thrust conditions up to a temperature ratio of 2.25. Beyond that point, the PDE values cross over the Brayton, and become slightly lower. The largest differences occur at the lower temperature ratios; that is below 2.25.

Specific Impulse

The specific impulse, I_{SP} (defined as the thrust per unit mass flow of fuel), for the stoichiometric propane/air mixture is shown in figure 9. Again, the I_{SP} for the PDE exceeds that of the Brayton cycle up to a temperature ratio of 2.25, at which point it falls below the Brayton cycle.

Forward Velocity Effect

The effect of forward speed is determined in accordance with the following relationship:[3]

$$\frac{F}{\dot{m}_0} = \frac{1}{g_c}\left[\sqrt{V_0^2 + 2\eta_{th}\tilde{q}c_P T_0} - V_0\right] \qquad (4)$$

Computations for 1000 and 2000 ft/s are shown in figures 10a and 10b.

A significant decrease in specific thrust is observed as the forward speed is increased. In figure 10a, the maximum value has dropped from 210 (figure 4b.) to a value of 175, and at 2000 ft/s the maximum specific thrust decreases to a value of 150 lbf-s/lbm. The PDE thrust advantage diminishes to zero at a temperature ratio of about 2.25.

Since ram compression occurs with forward flight speed, the value of ψ must be larger than 1. For a V_0 = 1000 ft/s the minimum value of ψ is about 1.2. Hence, the specific thrust advantage of the ideal PDE over the range of ψ is substantially reduced. At 2000 ft/s the minimum value of ψ is approximately 1.5 and no significant specific thrust advantage remains for the PDE cycle.

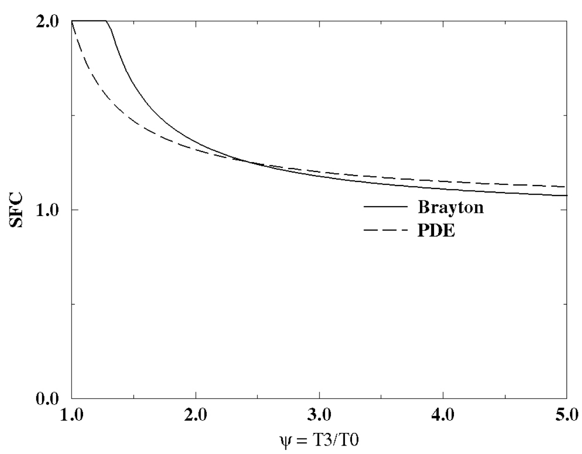

Figure 8. Specific fuel consumption (lbm/hr-lbf) for stoichiometric propane/air, γ =1.25, V_0 =0.

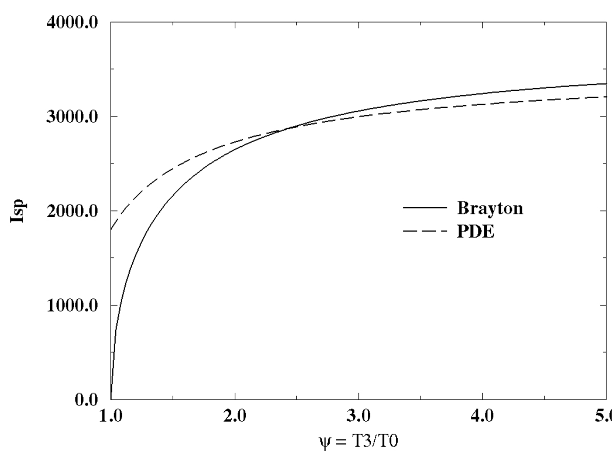

Figure 9. Specific Impulse (s) for stoichiometric propane/air, V_0 =0.

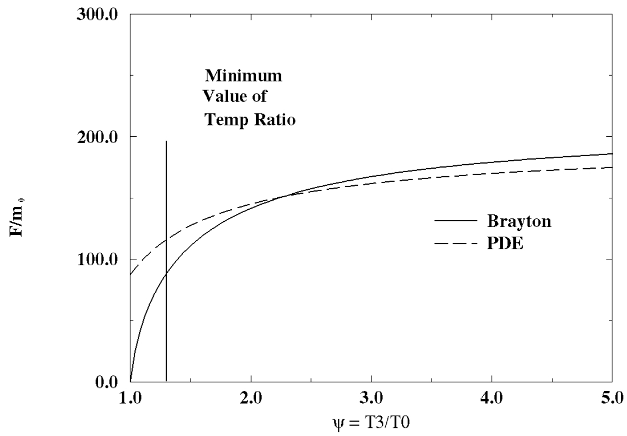

Figure 10a. Specific thrust per unit mass flow (lbf-s/lbm), V_0 = 1000 ft/sec, $\gamma = 1.25$, stoichiometric propane/air.

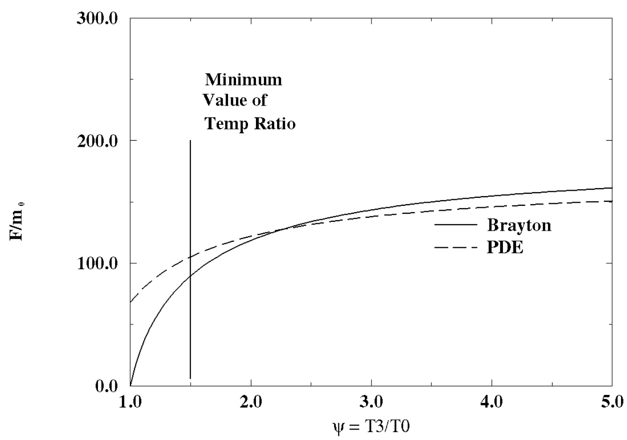

Figure 10b. Specific thrust per unit mass flow (lbf-s/lbm), V_0 =2000 ft/s, $\gamma = 1.25$, stoichiometric propane/air.

Performance at T_3/T_0=1 Operating Point

The importance of the reduced sensible heat release can also be demonstrated in any of the figures shown in this paper. For example, in figure 4b, which is the result for a static condition (V_0 =0), the Brayton cycle will perform as well as the PDE cycle with a ψ (= T_3/T_0) of only 1.3. This value corresponds to a compressor pressure ratio of only 2.5. In figure 10b, which presents the result for a forward velocity of 2000 ft/s, equivalent specific thrust is again obtained for the Brayton cycle with a temperature ratio of only 1.3.

Conclusions

The sensible heat release in both a detonation cycle engine (PDE) and a deflagration cycle engine (Gas Turbine) was determined using an equilibrium calculation. The sensible heat was then used in a thermodynamic cycle analysis to determine the maximum theoretical performance achievable. Based on those results, it was concluded that the significantly higher temperatures present in the detonation engine lead to dissociation losses that are 10 percent higher than in the turbine engine. Accounting for only the dissociation loss, the thermal efficiency of the ideal PDE remains significantly higher than the turbine engine cycle. The thrust per unit mass flow for the PDE also is greater than the Brayton cycle up to temperature ratios of 2.25. Beyond that number, the PDE value crosses over the Brayton value and remains slightly lower throughout the range. The specific fuel consumption is also lower than the gas turbine up to a temperature ratio of 2.25. And the specific impulse of the PDE exceeds that of the Brayton cycle up to a temperature ratio of 2.25.

Propane/air mixtures with equivalence ratios of 1 and 1.1 were used in this study. The specific thrust for both ratios showed no significant difference. Specific thrust was also calculated for acetylene/air and hydrogen/air mixtures, with the same general levels and trends.

The effect of forward flight speed was shown to reduce the specific thrust level significantly as well as the difference in value between the PDE and Brayton cycles. From a performance point of view, the PDE thrust, SFC and I_{SP} benefits are the highest at low temperature ratios (i.e., less than 2) but are substantially diminished at higher velocities. At a flight speed of 2000 ft/s the specific thrust advantage of the PDE no longer exists.

It is noted that PDE performance at low velocities is ideal for producing static thrust.

Finally, it is noted that the PDE may have other practical engineering advantages over a gas turbine engine, i.e., simplicity, fewer moving parts, lighter weight and lower cost. In order to realize these benefits, a number of issues are being addressed currently. These include the effects of high temperature and high internal flow velocity on heat transfer and viscous losses as well as fatigue and leakage issues related to cyclical operation and valving. These attributes and concerns were not addressed by the cycle analysis presented in this paper and must await practical demonstration.

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