Journal of Propulsion and Power
Vol. 18, No. 1, January–February 2002

Fundamentals of Idealized Airbreathing Pulse-Detonation Engines

J. A. C. Kentfield*
University of Calgary, Calgary, Alberta T2N 1N4, Canada

The intent of the paper is to establish a relatively simple procedure for evaluating the idealized performance potential of a pulse-detonation engine (PDE) intended for the jet propulsion of air vehicles. The study focuses, exclusively, on PDEs using atmospheric air as the oxidant. The study is based on the proposition that, because of the very fast wave action, an idealized model of a PDE can be regarded as a tubular containment (detonation tube) that is, during combustion, effectively closed at both ends. Furthermore, the maximum possible energy available is that derivable from combustion, at constant volume, of the tube reactants regardless of details of the mode, or modes, of combustion in the detonation tube. This implies, therefore, that in order to establish the idealized performance of a PDE it is possible to avoid becoming engrossed in details relating to the detonation wave itself. Conclusions from the study are that major initial charge nonuniformities do not appear to have a significant impact on idealized PDE performances and that the idealized performances of PDEs improve with increasing flight Mach number.

Nomenclature

$\bar{F}$	=	thrust (averaged over outflow)
$\bar{f}$	=	air-to-fuel ratio by mass
g_0	=	gravitational factor (unity and dimensionless in SI units; ft $lb_m/lb_f \cdot s^2$ in British units)
H	=	higher calorific value of fuel
M	=	(flight) Mach number
m	=	mass
P	=	absolute pressure
R	=	characteristic gas constant
T	=	absolute temperature
$\bar{U}$	=	kinetic-energy-averaged velocity
V	=	volume
γ	=	adiabatic index (1.4 for air; 1.35 for products)
ϕ	=	equivalence ratio
$\bar{\phi}$	=	charge (or reactants)—averaged value of ϕ

Subscripts

A	=	air
AMB	=	ambient
D	=	discharged
(HIGH)	=	high temperature value
JET	=	PDE jet flow
(LOW)	=	low temperature value
MAX	=	maximum value
P	=	products (of combustion)
R	=	residual

Introduction

PERHAPS the earliest non-piston-engine-type prime mover employing constant volume combustion, with a deflagrative and not a detonative reaction, was the Holzwarth gas turbine manufactured by Brown-Boveri (now ABB) in Switzerland during the early part of the last century.[1,2] Although Holzwarth-type gas turbines appeared to have had limited success, the technology was revisited in the 1970s in Australia employing newer, and improved gas turbine technology.[3–5] A point noted by the Australian workers was a drop in turbine efficiency, compared with that of conventional gas turbines, as a result of the wide range of turbine inlet conditions associated with the large cyclic variation of turbine inlet pressure caused by the combustion blowdown following substantially constant volume combustion.[4,5]

Yet more recent work with substantially constant volume combustion, or the equivalent, has concentrated on the development of the so-called pulse-detonation-engine (PDE) in which combustion is carried out via the mechanism of a detonation wave. This activity has been supported, as was the earlier gas-turbine work, by both theoretical and experimental approaches.[6,7] The PDE concept appears to be developing along two avenues. One approach uses conventional hydrocarbon fuel reacted with air with, in some cases, a small, localized, oxygen addition to promote the rapid formation of a detonation wave. The other approach employs oxygen as the oxidant in conjunction with a specialized fuel such as hydrogen. The latter system is more correctly identified not as a PDE but as a pulse-detonation-rocket engine.[8]

The objective of the present work is to attempt to establish the ideal performances, in a general indicative manner, of airbreathing, hydrocarbon-fueled, PDEs.

Outline of Theory

For the purposes of the idealized modeling of a PDE, the device is envisaged as a pipe or tube (i.e., the detonation tube) of uniform cross-sectional area connecting the upstream, or inlet end, of the engine with the downstream, or discharge, end of the device. Notionally instantaneously operating flow cutoff valves are assumed to be located at the ends of the detonation tube. The upstream valve is used to cutoff the air, and fuel, supply to inhibit backflow, from the inlet, during operation. This valve represents, at least in part, reality where pulsed valves are employed to regulate the supply of fuel, and localized oxygen injection when the latter is employed, and a valve may or may not be provided to prevent backflow from the air inlet. The notional downstream valve is provided to prevent premature escape of reactants and combustion products and, for dynamic operation, to permit the achievement of ram compression. In a real PDE, in which the detonation wave propagates from the inlet end, an outlet valve is unnecessary, at least for static or low forward speed operation because the arrival of the detonation front at the discharge end is the event initiating (significant) outflow.

Presented as Paper 2000-3469 at the AIAA/ASME/SAE/ASEE 36th Joint Propulsion Conference, Huntsville, AL, 16–19 July 2000; received 6 October 2000; revision received 20 July 2001; accepted for publication 18 September 2001.

*Professor, Department of Mechanical and Manufacturing Engineering, 2500 University Drive, N.W. Member AIAA.

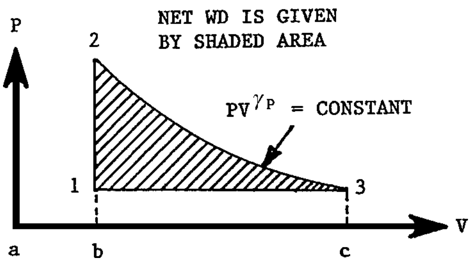

Fig. 1 Idealized network done during blowdown of a pressurized combustion space (detonation tube). The network done is shown shaded on the PV plane.

At the commencement of a cycle, the detonation tube is scavenged by flowing air, and fuel, into the inlet end while discharging residual products of combustion from the discharge end with both notional inlet and outlet valves fully open. Because for static operation the static pressures at the detonation tube inlet and outlet are equal, the volume flowed equals; for the ideal case the volume of the detonation tube the flow work terms each represented by a pressure volume (PV) term are equal for inflow and outflow and thus cancel. Hence the only import of energy into the detonation tube is represented by the sum of the inflow of internal energy, net kinetic energy, and the chemical energy potential of the unreacted fuel. For static operation the assumption is made that the net kinetic energy input caused by scavenge is zero.

Because a detonative combustion is, in energy terms, equivalent in an enclosed volume, when the wave action has decayed and the products of combustion are at rest, to a constant volume combustion process, the latter was employed to model the chemical reaction within the detonation tube. It has been shown that the easily modeled surrogate idealized constant volume combustion process results in a performance efficiency nearly identical to that of an idealized PDE performance modelled using a Zel'dovich, von Neumann, Doering (ZND)-type (shock wave followed by Rayleigh constant area combustion) detonation wave, the difference resulting in an efficiency ratio of only about 1.05 in favor of the use of an idealized detonation-wave model. The subsequent outflow established by instantaneous opening of the notional outlet valve was taken to result in an expansive discharge the work so obtained being converted reversibly into kinetic energy. The expansion process, external to the invariant-volume detonation tube, is illustrated diagrammatically on the PV plane in Fig. 1. It can be shown that, with reference to the notation of Fig. 1, the ideal work done (WD) from the detonation tube outflow is given by the shaded area of Fig. 1:

$$\mathrm{WD} = \int_2^3 P\,\mathrm{d}V - P_1(V_3 - V_2) \tag{1}$$

which can be shown to yield the result

$$\mathrm{WD} = P_1\left\{\left[\frac{(P_2/P_1)V_b - V_c}{\gamma_p - 1}\right] - (V_c - V_b)\right\} \tag{2}$$

where

$$P_2/P_1 = (V_c/V_b)^{\gamma_P} \tag{3}$$

Because the work done is equated to the kinetic energy of the jet,

$$\mathrm{WD} = \frac{m_D \bar{U}_{\mathrm{JET}}^2}{2g_0} \tag{4}$$

where m_D is the mass discharged. Thus for static operation the thrust $\bar{F}$ per unit mass of reactants (i.e., specific thrust or specific impulse) is given by

$$\bar{F} = \frac{m_D \bar{U}_{\mathrm{JET}}}{(m_D + m_R)g_0} \tag{5}$$

where m_R is the residual mass in the detonation tube at the surroundings pressure P_1. Also g_0 in Eqs. (4) and (5) is unity and dimensionless in the Système International unit system. It can also be shown that

$$m_R/(m_D + m_R) = (P_1/P_2)^{1/\gamma_P} \tag{6}$$

and

$$m_D + m_R = P_1 V_b / R T_1 \tag{7}$$

The relationship between T_2 and T_1 is the result of constant volume heat addition (i.e., combustion) and involves the higher calorific value H of the hydrocarbon fuel (taken as 46.5 MJ/kg or 20,000 Btu/$\mathrm{lb_m}$), the air-to-fuel ratio by mass f, the equivalence ratio ϕ, and the characteristic gas constant R. Thus,

$$T_2 - T_1 = \frac{\phi H(\gamma_P - 1)}{R_P f} \tag{8}$$

Equations (2–8) are manipulated and evaluated to establish the ideal static performances of PDEs. A double application was necessary when evaluating PDE performances with nonuniformities of temperature and or pressure within the detonation tube following assumed instantaneous combustion prior to instantaneous opening of the notional discharge valve.

Predicted Static Performance

Figure 2 presents the predicted performance obtained when the detonation tube is assumed to be filled with uniformly distributed reactants. The equivalence ratio range explored is $0.2 \le \phi \le 1.0$. Probable combustion difficulties at low ϕ values are, for the purposes of the investigation, ignored. The solid lines are likely to be pessimistic because the assumption is made that the blowdown leaves a residual mass of combustion products in the detonation tube at ambient pressure. On the other hand, the dotted curves are optimistic because they are based on the assumption that all of the mass in the detonation tube contributes to the jet kinetic-energy term (i.e., $m_R = 0$). The specific impulses are plotted in units of pounds force per second/pound mass, which reduces, when the $\mathrm{lb_f}$ and $\mathrm{lb_m}$ terms are canceled numerically or ignored, giving the familiar commonly used seconds units. In SI specific impulse is expressed in units of Newtons-second/kilogram, where 9.806 Ns/kg = 1 $\mathrm{lb_f \cdot s/lb_m}$. It is perhaps worth noting that Newtons-second/kilogram reduces, dimensionally, to a velocity, i.e., meter/second. The lower portion of

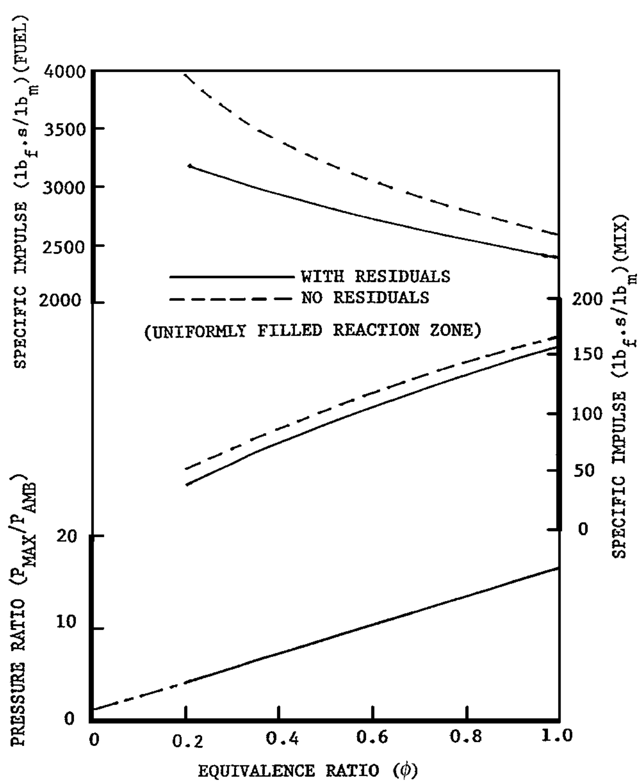

Fig. 2 Specific impulses and corresponding pressure ration vs equivalence ration following homogeneous, deflagrative combustion.

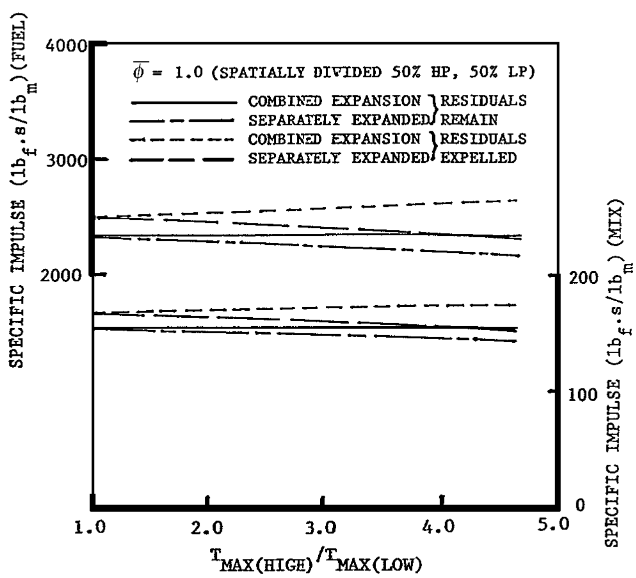

Fig. 3 Specific impulses vs temperature ration following nonhomogeneous deflagrative combustion. Combustion zone in two equal portions ($\phi = 1.0$).

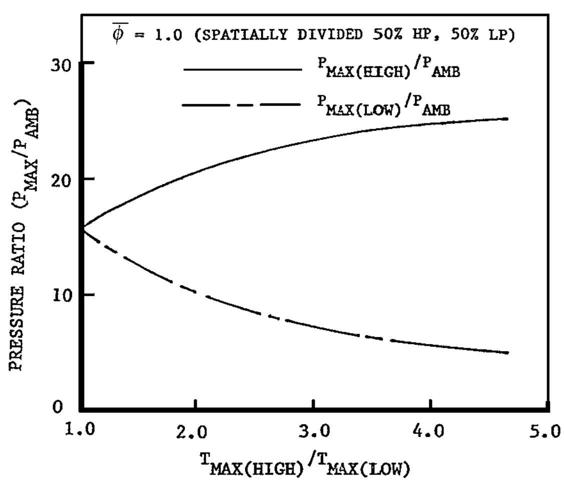

Fig. 4 Instantaneous pressure ratios, corresponding to Fig. 3, in each half of combustion zone.

Fig. 2 presents the uniform pressure ratios generated by deflagrative constant volume combustion. No attempt was made, in the results presented in Fig. 2, to simulate nonuniform postcombustion temperature and pressure conditions reminiscent, in part at least, of postdetonative combustion situations.

Figures 3–8 present data in which strong instantaneous nonuniformities are generated, by (assumed instantaneous) deflagrative combustion, in both postcombustion temperatures and pressures within the detonation tube as a result of assumed nonuniform fuel distributions in the charge air. Where the local fuel/air ratio exceeds normal combustion limits, a small oxygen addition can be assumed to have been added to fuel-rich zones. Correspondingly potential combustion difficulties in fuel-depleted zones are ignored in the elementary analytical treatment. Figures 3 and 4 present data for an average equivalence ratio $\bar{\phi}$ within the detonation tube of unity, whereas Figs. 5–8 are inclusive for a $\bar{\phi}$ value of 0.5. Figures 3–6 cover cases in which the rich- and weak-mixture strength zones each occupy 50% of the detonation tube volume. Figures 5 and 6 cover an extended temperature ratio range in an attempt to clarify, with $\bar{\phi} = 0.5$, the trends relating to variation of tube postcombustion temperature ratio observed in Figs. 3 and 4 with $\bar{\phi} = 1.0$. Figures 7 and 8 illustrate the consequence, also with $\bar{\phi} = 0.5$, of reducing the rich-mixture zone to 20% of the detonation tube volume with the remaining 80% containing the fuel-depleted, or weak, mixture.

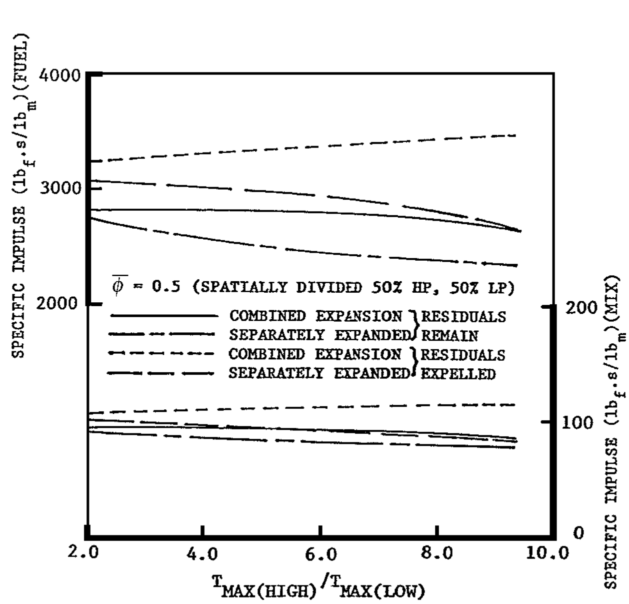

Fig. 5 Similar data to that of Fig. 3 but for $\phi = 0.5$.

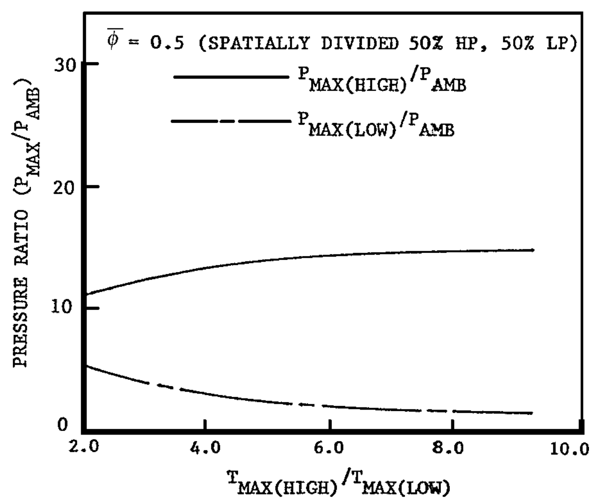

Fig. 6 Instantaneous pressure ratios, corresponding to Fig. 5, in each half of combustion zone.

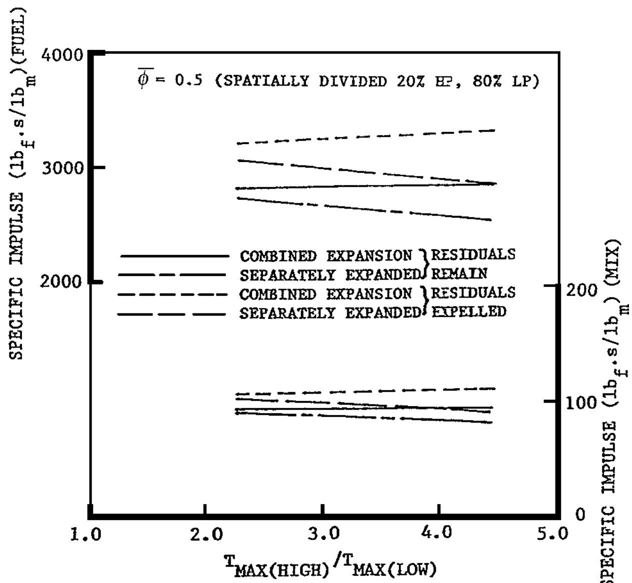

Fig. 7 Similar data to that of Fig. 3 but for $\phi = 0.5$ and the combustion zone unequally divided: 20% high temperature and pressure, 80% low temperature and pressure.

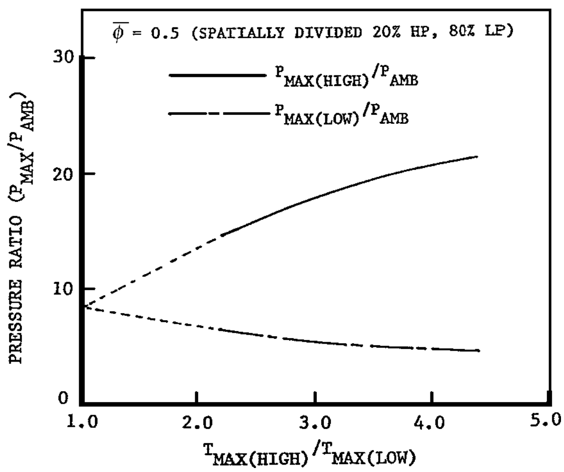

Fig. 8 Instantaneous pressure ratios, corresponding to Fig. 7, in the high- and low-temperature portions of the combustion space.

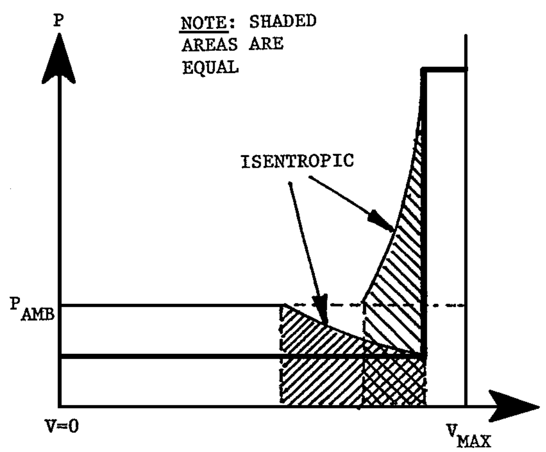

Fig. 9 Diagrammatic illustration, on a PV plane, of a hypothetical, thermodynamically reversible, pressure-splitting (or bifurcating) process within a detonation tube of internal volume $V_{\max}$.

Another hypothetical situation investigated involved a precombustion bifurcation of charge pressure, in which the total charge internal energy remained unaltered, by a process that resulted in the isentropic expansion of a portion of the charge from the ambient pressure to a lower pressure the work so obtained being employed to compress, isentropically, the remainder of the charge to a pressure higher than that of the ambient. Figure 9 illustrates diagrammatically such a hypothetical process on a PV plane representing the interior of a detonation tube of maximum volume $V_{\max}$. The final status of the charge, prior to combustion, is illustrated by means of the thick solid line. For the particular example illustrated, the high-pressure charge occupies 10% of the volume of the detonation tube, and the low-pressure portion of the charge the remaining 90% of the volume of the detonation tube. When the low-pressure material is expanded to half the ambient pressure, it is found that the high-pressure material is increased in pressure to 3.365 times the ambient pressure. The corresponding temperatures as fractions of the ambient temperatures are 0.820 and 1.414 in the low- and high-pressure regions, respectively. It is also found that the initial charge at ambient pressure and temperature occupies only 78.65% of the detonation tube total volume. The results obtained for the foregoing circumstances are illustrated, for $\overline{\phi} = 0.5$, in Figs. 10 and 11. The general character of the specific-impulse-vs-temperatue ratio information presented in Fig. 10 is similar to that obtained with temperature-only induced nonuniformities in the detonation tube as illustrated in Figs. 3, 5, and 7.

In an attempt to investigate the potential of a detonation wave to yield a performance improvement, not noted in the review of the

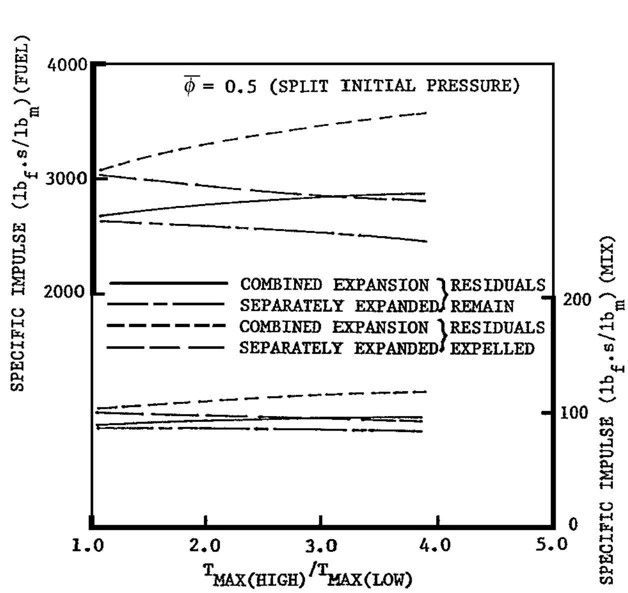

Fig. 10 Specific impulses, achieved with the superposition of pressure bifurcation and temperature nonuniformities, vs temperature ratio ($\phi = 0.5$.) with the combustion zone unequally divided: 10% high temperature and pressure, 90% low temperature and pressure.

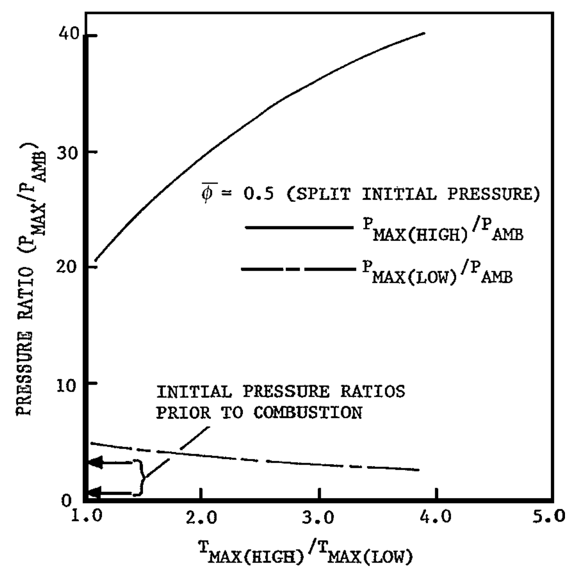

Fig. 11 Instantaneous pressure ratios, corresponding to Fig. 10, in the high- and low-temperature portions of the combustion space.

influences of various nonuniformities explored previously and presented in Figs. 3, 5, 7, and 10, detonation waves were studied analytically for two cases with a detonation tube, homogeneously charged, when $\overline{\phi} = 1.0$ and 0.5. Simple, classical, ZND-type detonation-wave analysis was applied to each case with the detonation wave being assumed to propagate through a fuel/air mixture at rest. The results of the analysis[9] showed that the benefits arising, in terms of thrust generation potential, were very small because, in part, of the low isentropic compression efficiency of the shock wave (0.25 when $\phi = 1$, 0.37 when $\phi = 0.5$) although this adverse influence was more than compensated by the relatively small entropy increase associated, for a moving shock, with the subsequent constant area (Rayleigh) combustion.

Predicted Dynamic Performance

In view of the relatively small influence on performance of detonation-tube preexpansion nonuniformities apparent in Figs. 3, 5, 7, and 10, the dynamic performance of an idealized PDE was evaluated on the basis of uniform constant volume combustion within

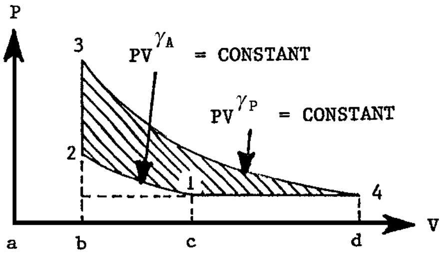

Fig. 12 Net idealized work done during blowdown, shown shaded on the PV plane, for dynamic operation of a simulated, idealized, PDE.

the detonation tube. The PDE dynamic performance was evaluated at the arbitrarily chosen altitude of 7.62 km (25,000 ft), where $T_1 =$ 238.5 K (429.3°F absolute) and the corresponding ambient pressure P_1 is 37.60 kPa (5.453 $lb_f/in.^2$ absolute). The net WD by the PDE is equated to the net kinetic energy available from the expanding exhaust flow and can be shown to be given, after intake ram compression is taken into account, by (with reference to Fig. 12)

$$\mathrm{WD} = P_1\left\{\left[\frac{(P_3/P_1)V_b - V_d}{\gamma_{p-1}}\right] - \left[\frac{(P_2/P_1)V_b - V_c}{\gamma_{A-1}}\right] - (V_d - V_c)\right\} \tag{9}$$

where

$$P_3/P_1 = (V_d/V_b)^{\gamma_P}, \qquad P_2/P_1 = (V_c/V_b)^{\gamma_A}$$

The relationship between pressure ratio P_2/P_1 achieved by an ideal intake and the flight Mach number M is given by the well-known relationship

$$P_2/P_1 = \left\{1 + [(\gamma_A - 1)/2]M^2\right\}^{\gamma_A/(\gamma_A - 1)} \tag{10}$$

Also, with reference to Fig. 12, Eq. (8) of the static performance analysis is replaced, for dynamic cases, by

$$T_3 - T_2 = \frac{\phi H(\gamma_P - 1)}{R_P f} \tag{11}$$

Figure 13 represents predicted net specific impulses vs flight Mach number M for $\phi = 1.0$ and 0.5 derived from use of Eqs. (9), (10), (4), (5), and (11). The possibility of residual mass remaining in the detonation tube under conditions of dynamic operation was discounted because of the dynamic head available to promote scavenge; hence, the residual mass m_R was taken to be zero. The flight-Mach-number range investigated was $0 \leq M \leq 2.0$. Clearly flight at zero Mach number is not a realistic case but was included merely to increase the range of flight conditions explored. Figure 14 shows the maximum cycle pressure ratios P_3/P_1, corresponding to the data of Fig. 13.

Figure 15 presents, vs flight Mach number on the left-hand ordinate, the product of mass per cycle multiplied by specific thrust, both based on the air-plus-fuel mass, normalized by the product of mass and specific thrust both for the zero Mach-number condition. On the right-hand ordinate a similar scale is used with the exception that the normalizing specific thrust is that for $M = 0$ and $\phi = 1.0$. This form of presentation results in three curves: two for the $\phi = 0.5$ case and a curve common to both ordinate scales for $\phi = 1.0$. The left-hand ordinate allows the relative thrust-producing effectiveness of $\phi = 0.5$ to be compared with that for $\phi = 1.0$. The right-hand ordinate allows the absolute predicted thrust-generation capabilities with $\phi = 0.5$ and 1.0 to be compared quantitatively.

Discussion

The dominant feature to emerge from the foregoing study is the apparent lack of influence, on thrust-generating performance, of the various simulated nonuniformities of the situations modeled as

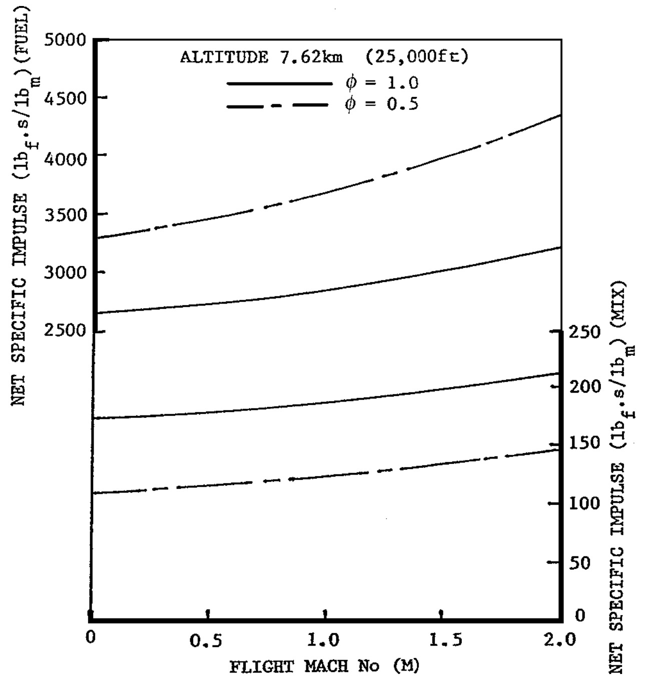

Fig. 13 Net specific impulse vs flight Mach number of idealized PDEs with simulated, homogeneous, combustion (ϕ = 0.5 and 1.0).

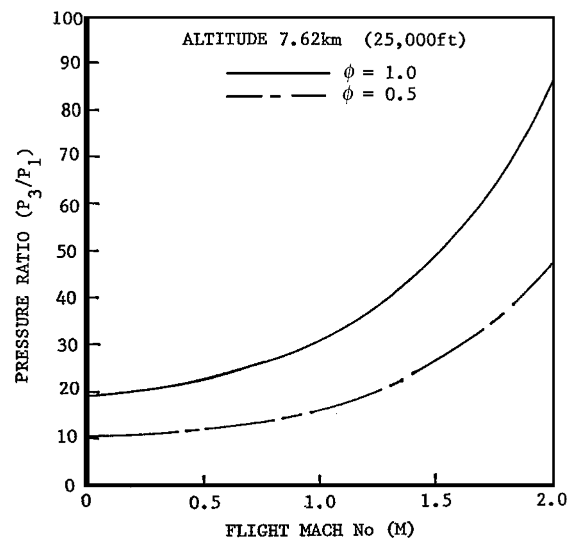

Fig. 14 Maximum pressure ratios corresponding to the data of Fig. 13.

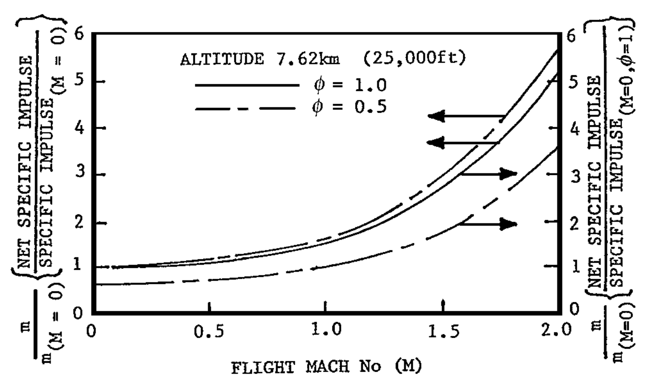

Fig. 15 Normalized specific thrust ratios, corresponding to the data of Figs. 13 and 14.

presented in Figs. 3–11. This suggests that the influence, on thrust performance, of the nonuniformities within the detonation tube created by a detonation wave may well, at best, be small. The curves of Figs. 3, 5, 7, and 10 drawn with short dashes are inherently optimistic because, in each case, the assumption was made that the outflow kinetic energy emerged as a homogeneous package with no allowance for mixing losses or the possibility of residual products of combustion remaining within the detonation tube prior to the scavenge process. The most pessimistic predictions are those, represented by a chain-dashed line, in which the high- and low-pressure portions of the postcombustion products were considered to each expand isentropically and separately to the surroundings pressure with residual combustion products, at ambient pressure, remaining within the detonation tube following the expansion process. Very approximately the average of the most optimistic and the most pessimistic predictions constitutes a horizontal, or nearly horizontal, trace on Figs. 3, 5, 7, and 10.

Flow Mach Number

The flow Mach number associated with the isentropic blowdown process ranges from a peak value of about three at the beginning of blowdown to subsonic values toward the end of the process with an average flow Mach number of about 1.5 or thereabouts. This range suggests, perhaps, a case for a plug nozzle a device noted for operational flexibility as a result of the freedom of the outer boundaries of the flow to adjust to instantaneous operational conditions. Possibly a plug in the outlet of a PDE can cause difficulties when the detonation wave reaches the outlet. An alternative, avoiding the plug problem, may be the use of what has been termed an "aerospike" nozzle by the rocket community. Such a nozzle has been proposed for the X-33 Advanced Technology Demonstrator rocket vehicle. A nozzle of the aerospike type eliminates the need for a plug located partly within the detonation tube. Care will have to be taken, for example, by the use of two PDE units firing simultaneously and exhausting along each face of a wedge-like body located between them to avoid the generation of unbalanced, pulsating, lateral forces (Fig. 16).

Engine Frequency

For a 1-m (3.25-ft) long detonation tube the scavenge duration time for static operation, even with a scavenge flow Mach number of 0.5, requires approximately 6 ms; the transmittal time for a detonation wave is in the region of 0.5 ms (Ref. 10). Hence the scavenge duration is approximately 12 times the combustion duration, and the maximum frequency, which is inversely proportional to the detonation tube length, is approximately 150 Hz (cycle/s). Under high-speed flight conditions it should be possible to reduce the scavenge duration by 50% resulting in a maximum frequency of about 285 Hz (cycle/s). However, effective intake ramming supercharging a PDE as assumed for the idealized dynamic analysis tends to act counter to a significant frequency increase.

Thrust Augmentation

The expected increase of firing frequency with increasing flight speed suggests the desirability of introducing thrust augmentation at low flight speeds and during takeoff in an attempt to compensate

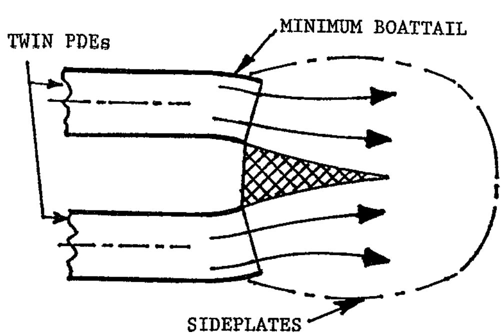

Fig. 16 Modified plug, or aerospike, thrust nozzle (diagrammatic).

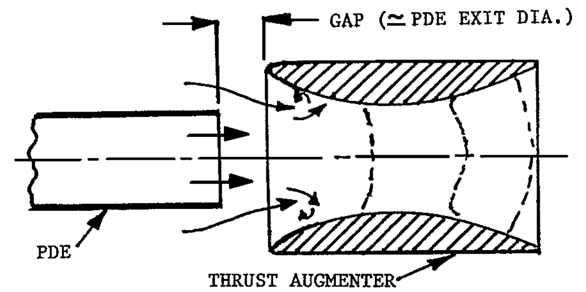

Fig. 17 Nonsteady-flow ejector-type augmenter (diagrammatic).

for the lower operational frequency at these operating conditions. Based on operational experience with primary flows generated by pulse jets, a French-developed convergent–divergent venturi-like, thrust-augmenter ejector might prove helpful.[11,12] Units of this type, which are not dependent upon viscous mixing of the primary and secondary flows for momentum transfer but rather on a plug-flow type interaction between an energetic, nonsteady, primary flow and the induced secondary flow, have been shown for pulse-jet type applications to produce static thrust augmentation ratios in the region of two with primary-to-ejector-throat area ratios of approximately 1:4. Ejectors of this type, illustrated diagrammatically in Fig. 17, have, however, been shown to become progressively less effective in pulse-jet applications as flight speed builds up. If such a problem arises when a PDE generates the nonsteady primary flow, the device can, perhaps, be jettisoned for missile or target-drone type applications or alternatively retracted into the PDE afterbody fairing.

Conclusions

The following main conclusions can be drawn from the study:

1) For static operation of an idealized PDE, the import, per cycle, of energy into the detonation tube is represented by the sum of the net internal energy, net kinetic energy, and the net chemical energy potential added during the scavenge/recharge phase of the cycle. The inlet and outlet flow-works (PV) terms cancel, provided the inlet and outlet pressures are those of the surroundings.

2) There appears to be, from a thrust-generating performance perspective, the lack of a significant sensitivity to nonuniformities in both temperature and pressure within the detonation tube during static operation. This suggests that the nonuniformities created by the passage of a detonation wave may also have but little influence on thrust generation. This conclusion was supported by a study of the influence on thrust performance of detonation waves in detonation tubes uniformly charged with reactants.

3) There is a strong potential for the performance of PDEs to improve with increasing flight Mach number, provided intake ramming can be utilized effectively. There is, in addition, the likelihood of another performance enhancement caused by an increase in cyclic (firing) frequency especially if an outlet flow-control valve is not employed.

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