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Thermodynamics of Airbreathing Pulse-Detonation Engines

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An analytical investigation was conducted of the idealized performance potential, from a thermodynamic cycle viewpoint, of airbreathing pulse-detonation engines (PDEs) primarily intended for air-vehicle propulsion. The investigation was restricted to the static operation of PDEs. The detonation-wave model used was of the classical Zel'dovich–von Neumann–Doering type, in which an initiating shock wave is followed by a Rayleigh-type combustion process in a duct, the detonation tube, of uniform cross-sectional area. The results of the analysis indicated that the idealized PDE performance was only slightly better than that of a simple, easily analyzed, constant-volume combustion, Lenoir-type surrogate cycle. The PDE also had the potential of being slightly more efficient, under idealized flight conditions, with induction ramming occurring, than the corresponding surrogate cycle. The corresponding surrogate cycle will advance thermodynamically, due to intake ramming, from a relatively inefficient Lenoir cycle to a more efficient Humphrey, or Atkinson, cycle.

Nomenclature

C_p	=	specific heat at constant pressure
C_v	=	specific heat at constant volume
G	=	Crocco Mach function [see Eq. (6)]
M	=	Mach number
N	=	Crocco Mach function [see Eq. (8)]
P	=	static pressure
P_0	=	stagnation pressure
S	=	entropy
T	=	static temperature
T_0	=	stagnation temperature
V	=	volume
γ	=	adiabatic index, $\frac{7}{5}$, also $\frac{9}{7}$
Δq	=	specific increment of energy input
Δs	=	entropy increment
ΔT	=	temperature increment
η	=	thermal efficiency
Ø	=	equivalence ratio

Subscripts

A, B, C, D, E	=	state points (see Figs. 2 and 3)
CV	=	constant volume
final exp	=	final expansion
gain	=	net temperature gain
KEgain	=	gain of kinetic energy
shock	=	due to shock wave
work	=	work obtained
X, Y, Z	=	state points (see Fig. 1)

Superscript

′	=	stationary wave conditions exclusively

Introduction

ALTHOUGH there is currently much interest in the potential of pulse-detonation engines (PDEs) as jet propulsors for flight applications and, perhaps to a lesser extent, as pressure-gain combustors for use in gas turbines, relatively little work appears to have been carried out on the fundamental thermodynamic analysis of airbreathing, hydrocarbon fueled, PDE cycles. However, interest in the practical use of detonation waves in combustion systems extends over a period in excess of 40 years.[1–4] The current paper presents relatively detailed, fundamental, idealized thermodynamic analyses of the static operation of hydrocarbon fueled PDE cycles.

The use of the term "cycle" in relation to a PDE has to be interpreted relatively carefully because a PDE is a nonsteady flow device, and, hence, not all molecules of the working fluid necessarily undergo identical processes. This characteristic is also common to other nonsteady flow systems, for example, wave rotors and pulse combustors. Nevertheless, a PDE operating cycle can be established based on fundamental considerations.

The detonation wave in a PDE is modeled as a shock wave, followed by combustion in a uniform cross-sectional area detonation tube, and does not take into account the influence of wall friction in the detonation tube. The combustion process is, thus, of the Rayleigh type. A detonation wave modeled in this classical manner is sometimes identified as a Zel'dovich–von Neumann–Doering (ZND) detonation wave. Analysis of a ZND-type model of a detonation wave was described by Foa[5] and was used in the thermodynamic treatment presented in the paper.

Detonation Wave Analysis

Foa's[5] analysis deals with a stationary shock front. The case of a moving shock is covered by converting the stationary wave to a moving wave by subtracting a velocity equal to the approach velocity of the freestream, for the stationary wave case, from all of the velocities derived from the stationary wave analysis, thereby yielding a situation in which the initial shock wave is advancing into reactants at rest in the detonation tube or combustor. This procedure, to change from a stationary wave to moving wave, does not alter the shock and combustion static pressure and temperature ratios, or the pre- and postcombustion event static pressures and temperatures for a specified initial static pressure and temperature.

The Foa[5] model is based on the condition that, for the stationary wave situation, the flow Mach number, relative to the stationary wave, is unity at the point where combustion is complete. This is known as the Chapman–Jouguet (CJ) condition, an essential condition for heat addition in a constant area duct, such as a detonation tube, when friction is ignored and the postshock flow Mach number is subsonic relative to the stationary wave. The latter is evaluated, via normal shock relations, on the basis of the strength of the shock wave. The connection between the strength of the initial stationary shock and the CJ condition applicable at the completion of combustion is provided, where Fig. 1 illustrates the notation used, by

$$(M_x')^2 \cong 2[1 + (\gamma + 1)(\Delta q / C_p T_x)] \tag{1}$$

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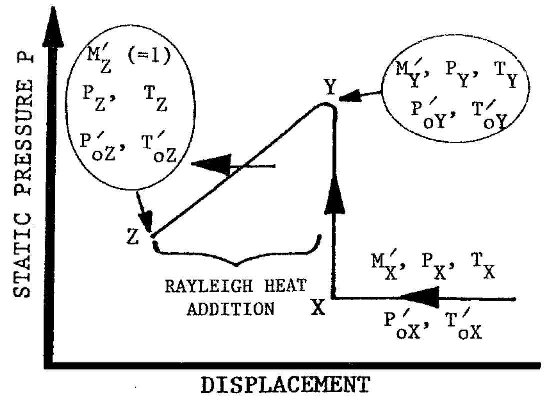
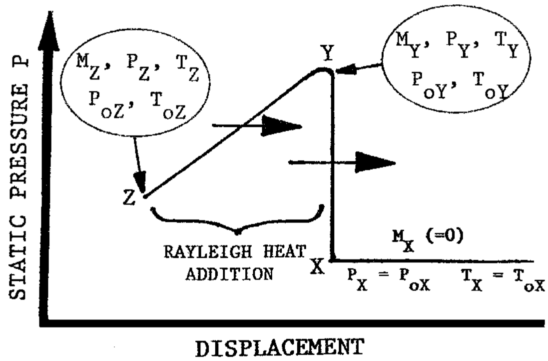


Stationary shock



Moving shock

Fig. 1 Detonation waves.

where Δq is the known increase of enthalpy due to combustion and T_x is also known.

The appropriate heat addition criterion for a Rayleigh process is one based on enthalpy. There is, at entry to the uniform cross-sectional area combustion zone, an input of flow work, kinetic energy, and an internal energy flow, with a corresponding situation prevailing at the outlet of the combustion zone. Thus, it is easy to show that the specific energy addition due to combustion is correctly described in terms of the stagnation temperature rise between the inlet and outlet stations, multiplied by the appropriate specific heat at constant pressure. Hence, with constant C_p,

$$\Delta q = C_p(T'_{0Z} - T'_{0Y}) \tag{2}$$

Hence,

$$M'_x \cong \{2[1 + (\gamma + 1)(T'_{0Z} - T'_{0Y})/T_x]\}^{\frac{1}{2}} \tag{3}$$

and from normal-shock relations,

$$\frac{P_Y}{P_X} = \frac{2\gamma M'^2_x - \gamma + 1}{\gamma + 1} \tag{4}$$

P_Y/P_X can, alternatively, be evaluated directly from normal-shock tables.

Also, from the work of Foa,[5]

$$P_Z/P_X = \tfrac{1}{2}[(P_Y/P_X) + 1] \tag{5}$$

for a Rayleigh heat addition process following an initiating normal shock. Furthermore, for a Rayleigh heat addition

$$P_o G = \text{const} \tag{6}$$

where

$$G \equiv \frac{1 + \gamma M'^2}{\{1 + [(\gamma - 1)/2]M'^2\}^{\gamma/(\gamma-1)}} \tag{7}$$

and

$$N\Big/\sqrt{T'_0} = \text{const} \tag{8}$$

where

$$N = \frac{M'\{1 + [(\gamma - 1)/2]M'^2\}^{\frac{1}{2}}}{1 + \gamma M'^2} \tag{9}$$

Thus, on the basis of a specified enthalpy addition, as in Eq. (2), M'_X is evaluated from Eq. (3) for a specified value of T_X. This, in turn, allows P_Y/P_X to be established either from Eq. (4) or directly by reference to shock tables for the appropriate values of M'_X and γ. Also, M'_y can be obtained from shock tables and, hence, T'_{0Y} can be evaluated, after establishing T_Y/T_X from shock tables, by use of the relationship

$$T'_{0Y}/T_x = (T_Y/T_x)\{1 + [(\gamma - 2)/2]M'^2_Y\} \tag{10}$$

Similarly, from knowledge of P_Y/P_x

$$P'_{0Y}/P_x = (P_Y/P_x)\{1 + [(\gamma - 2)/2]M'^2_Y\}^{\gamma/(\gamma-1)} \tag{11}$$

The Mach number functions G and N are, for convenience, presented graphically by Foa.[5] These relationships were derived by Crocco[6] and allow Eq. (6) to be solved very easily with the appropriate value of the constant as established from knowledge of T'_{0Y} from Eq. (10). This then allows T'_{0Z} to be obtained from a further application of Eq. (8) for the condition $M'_Z = 1.0$.

Likewise, the constant of Eq. (6) can be evaluated based on the known values of M'_y and P'_{0y} [see Eq. (11)]. This permits P'_{0z} to be established from Eq. (6) for the known value of the constant when $M'_Z = 1.0$. It is then easy to check the result obtained for P_Z/P_X from Eq. (12):

$$P_Z/P_X = P'_{0Z}/P_X \cdot \{1 + [(\gamma - 1)/2]M'^2_Z\}^{-\gamma/(\gamma-1)} \tag{12}$$

with the value of P_Z/P_X obtained from Eq. (5).

The conversion of the stationary wave results to those applicable to a moving wave was based on reevaluation of the stagnation conditions at the three stations after subtraction of the velocity approaching station X for the stationary wave case from the velocities at stations X, Y, and Z. This implied, for unchanged static conditions at station X, the results

$$M_X = 0, \qquad P_X = P_{0X}, \qquad T_X = T_{0X} \tag{13}$$

with the static pressure and temperature ratios, namely,

$$P_y/P_x, \qquad P_z/P_x, \qquad T_y/T_x, \qquad T_z/T_x$$

remaining unaltered from the stationary wave case.

The increase of entropy due to the shock wave component of the detonation wave alone is given, based on a commonly used expression available in thermodynamic texts, for invariant specific heat cases by

$$\Delta S_{XY} = C_p \ln(T_{0Y}/T_X) - (C_p - C_v)\ln(P_{0Y}/P_X) \tag{14}$$

and, similarly, for the constant area combustion process alone by

$$\Delta S_{YZ} = C_p \ln(T_{0Z}/T_{0Y}) - (C_p - C_v)\ln(P_{0Z}/P_{0Y}) \tag{15}$$

When Eqs. (14) and (15) are converted to a dimensionless form by dividing by a specific heat, for example, at constant pressure, Eq. (14) becomes

$$\Delta S_{XY}/C_p = \ln(T_{0Y}/T_X) - [(\gamma - 1)/\gamma]\ln(P_{0Y}/P_X) \tag{16}$$

Correspondingly, Eq. (15) becomes

$$\Delta S_{YZ}/C_p = \ln(T_{0Z}/T_{0Y}) - [(\gamma - 1)/\gamma]\ln(P_{0Z}/P_X) \tag{17}$$

Also, for a direct overall measure of the dimensionless entropy increment associated with a detonation wave as a whole,

$$\Delta S_{XZ}/C_p = \ln(T_{0Z}/T_X) - [(\gamma - 1)/\gamma]\ln(P_{0Z}/P_X) \tag{18}$$

Energy Distribution

The detonation wave is assumed to propagate from the head end of the detonation tube. It is further assumed that the tube can be closed off, for example, by an automatic nonreturn valve, or possibly by a rotary valve as proposed by Edwards[2] and later by Bussing.[7] Thus, the detonation advances toward the exit end of the detonation tube. It is further assumed that the detonation wave is initiated instantaneously. Therefore, without the need for a growth length, the shock front traverses the entire length of the detonation tube and, hence, progressively interacts with, compresses, and accelerates all of the initial contents (reactants) of the detonation tube. Because the station denoting the completion of combustion lags behind the initial shock, combustion has not been completed at the instant the shock wave reaches the exit station of the detonation tube.

Furthermore, the expansion wave propagating from the closed inlet face of the detonation tube can not, in general, have fully expanded the reaction-tube contents. There exists, therefore, a relatively complex situation in which the pressure and temperature in the reaction tube are each nonuniform. This results in a meaningful average pressure being substantially lower than the peak pressure, adjacent to the tube exit, resulting from the normal shock that precedes the Rayleigh combustion. Also, a meaningful average temperature is substantially lower than that resulting from the Rayleigh combustion process. The problem is, therefore, to find a way to resolve this situation. A clue is to consider an energy balance in the reaction tube based on the energy required to power, or drive, the detonation wave. This procedure avoids the need to specify a mean pressure, and also a mean temperature, of the reaction-tube contents. It does not, however, lead to an explicit evaluation of the kinetic energy within the detonation tube. Thus, the enthalpy increase due to constant area combustion, with a constant specific heat for the moving detonation wave case, is

$$\propto (T_{0Z} - T_{0Y}) = \Delta T_{\text{gain}} \tag{19}$$

Note that $(T_{0Z} - T_{0Y})$ for the moving wave is less than $(T'_{0Z} - T'_{0Y})$ for the stationary wave situation. Work obtained and employed to power the shock wave is established on the basis of the energy released by combustion Δq minus the enthalpy increase represented by Eq. (19), that is,

$$\propto [\Delta q/C_p - \Delta T_{\text{gain}}] = \Delta T_{\text{work}} \tag{20}$$

ΔT_{work} includes a contribution due to the gain of kinetic energy within the detonation tube.

However, work required to drive the normal shock compression and gas acceleration process,

$$\propto (T_{0Y} - T_X) = \Delta T_{\text{shock}} \tag{21}$$

Therefore, the work that must be extracted from the final isentropic expansion to provide an energy balance is

$$\propto (\Delta T_{\text{shock}} - \Delta T_{\text{work}}) = \Delta T_{\text{final exp}} \tag{22}$$

and, thus, the final temperature constituting the starting point for useful net work extraction is given by (Fig. 2)

$$(T_{0Z} - \Delta T_{\text{final exp}}) = T_D = T_{0D} - \Delta T_{\text{KEgain}} \tag{23}$$

Hence, T_{0D} is greater than T_D by the magnitude of ΔT_{KEgain}.

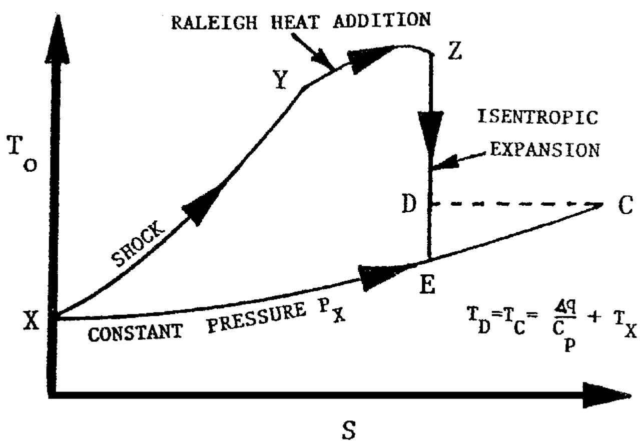


Fig. 2 Detonation wave and subsequent expansion on a stagnation temperature–entropy plane.

When an energy input Δq is provided for the constant area, Rayleigh combustion in the detonation wave, and a simple heating process at constant pressure with zero kinetic energy at state C,

$$T_D = T_C \tag{24}$$

The result represented by Eq. (24) is shown notationally in Fig. 2. Quantitative confirmation of this result is given later. Equation (24) follows as a consequence of the nature of the heat addition paths for the PDE and simple constant pressure processes.

Constant Volume Surrogate Cycle

An approximate surrogate cycle for a PDE operating statically is a simple, constant-volume heat addition cycle known as a Lenoir cycle. In this case, heat addition occurs at constant volume from state X, that is, P_X and T_X, with, for comparative purposes, a heat addition equal to the heat addition at constant pressure. Hence, the constant-pressure heat addition temperature rise is replaced by a greater temperature rise of $\Delta q/C_V$ from temperature T_X to T_A, which is both a static and a stagnation temperature because state A represents a zero velocity condition. Note that the dimensionless entropy increment for the constant-volume heat addition is represented by

$$\Delta S_{XA}/C_p = (1/\gamma) \ln(T_A/T_X) \tag{25}$$

where

$$T_A = (\Delta q/C_v) + T_x \tag{26}$$

The constant-volume cycle is shown, notationally, in Fig. 3.

Because the work obtained results from expansion of the contents of the combusted reactants, the work obtainable corresponds to the drop of internal energy only, minus flow work against the surroundings, and not to an enthalpy drop. This is illustrated in Fig. 4 in the form of a pressure-volume (PV) diagram for flow leaving and,

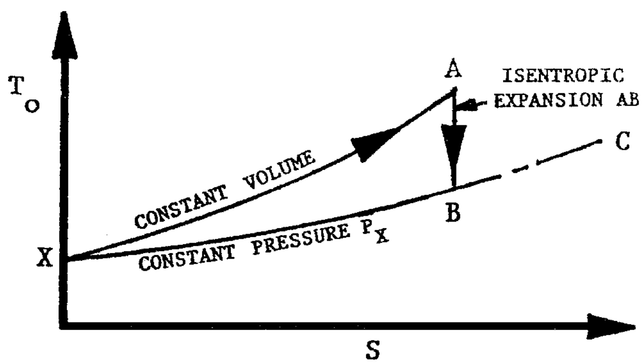


Fig. 3 Surrogate constant-volume-combustion (Lenoir) cycle on a stagnation temperature–entropy plane.

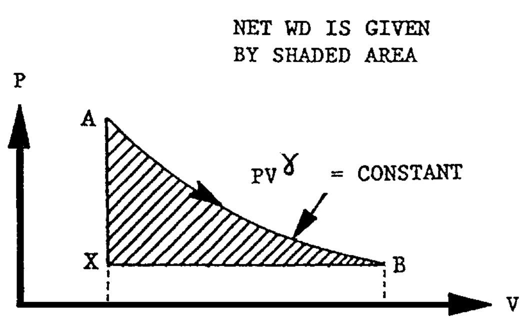


Fig. 4 Idealized net work done during blowdown of a pressurized combustion space (detonation tube), the net work done is shown shaded on the PV plane.

therefore, external to, the detonation tube. The work done (WD) by the expansion is given by

$$\mathrm{WD} = \int_A^B P\,\mathrm{d}V - P_x(V_B - V_A)$$

$$= P_X\left\{\left[\frac{(P_A/P_X)V_X - V_B}{\gamma - 1}\right] - (V_B - V_X)\right\}$$

which, in turn, can be reduced to the more useful result

$$\mathrm{WD} = C_v(T_A - T_X) - C_p(T_B - T_X) \tag{27}$$

It is shown later that the entropy increase for an equal energy addition is slightly greater for the idealized constant-volume cycle than for an idealized detonation-wave driven PDE.

Results

Four specific cases were studied for equivalence ratios Ø of 1.0, 0.75, and 0.5 with $\gamma = 1.4$, that is, $\frac{7}{5}$, and one case for Ø = 0.75 with $\gamma = 1.2857$, that is, $\frac{9}{7}$. In every case, γ was assumed to be constant over each idealized cycle investigated. The higher calorific value of the fuel was taken as 46.5 MJ/kg (20,000 Btu/lbm) giving a temperature rise of $(T'_{0Z} - T'_{0Y}) = 3112$°C with Ø = 1.0 and $\gamma = 1.4$ for heating at constant pressure. The temperature rise was reduced proportionally as Ø was reduced. For the $\gamma = 1.2857$ case adjustment, based on the results of Ellenwood et al.,[8] the specific heat at constant pressure resulted in an expected temperature rise of 2441°C with Ø ≅ 1.0. Again, the expected temperature rise would be reduced in proportion to the value of Ø employed. Figures 5–7 present the results, on a stagnation basis, for Ø = 1.0, 0.75, and 0.5, respectively.

The curvatures of the normal shock and Rayleigh constant-area heating characteristics were established by interpolative use of the analytical procedures described earlier. The "humped" nature of the Rayleigh heating characteristics *YZ* reflect the well-known phenomenon of the maximum temperature exceeding that prevailing at the completion of the heat addition process. However, this phenomenon is somewhat augmented in magnitude, and shifted to the left, for the moving wave relative to that occurring with a stationary wave. Figure 8 shows the results obtained for $\gamma = 1.2857$ and Ø = 0.75.

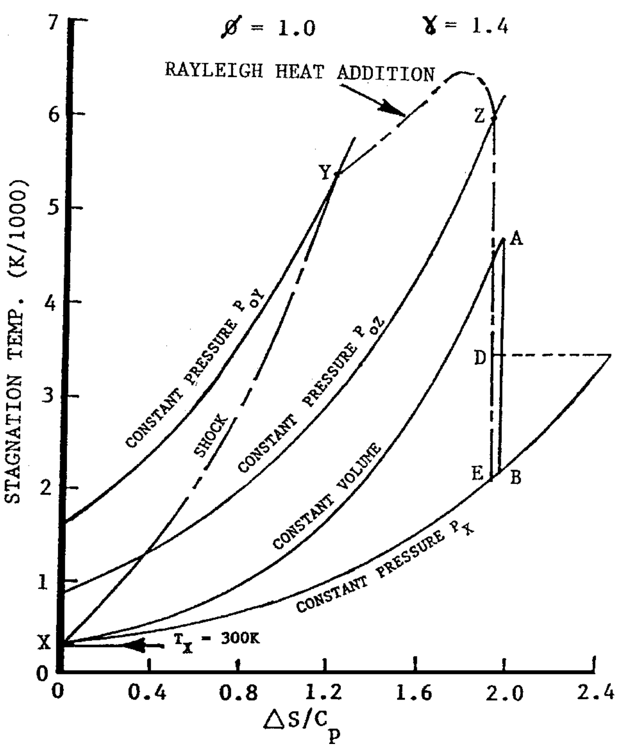


Fig. 5 Temperature–entropy diagram for idealized PDE and comparable Lenoir cycle: equivalence ratio Ø = 1.0 and γ = 1.4; state points, except state point *D*, based on stagnation values (static operation).

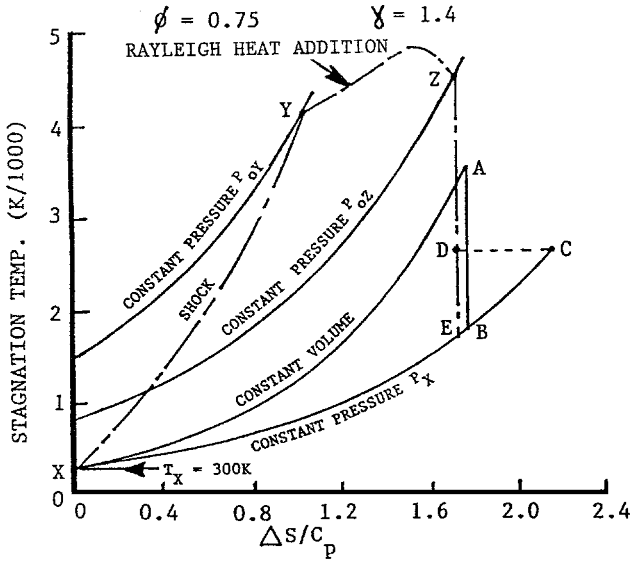


Fig. 6 Temperature–entropy diagram for idealized PDE and comparable Lenoir cycle: equivalence ratio Ø = 0.75 and γ = 1.4; state points, except state point *D*, based on stagnation values (static operation).

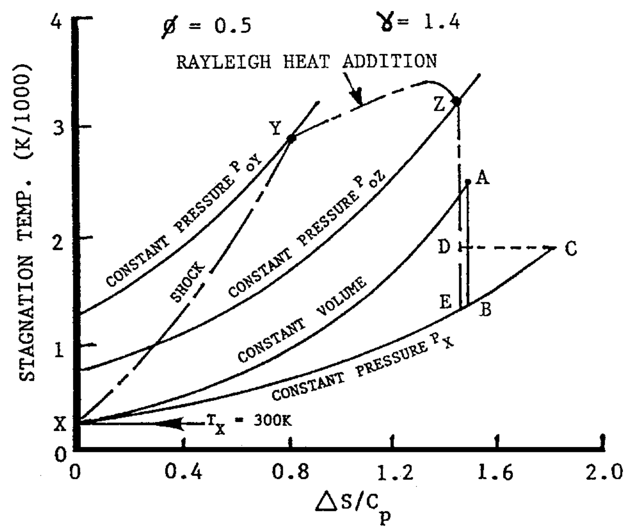


Fig. 7 Temperature–entropy diagram for idealized PDE and comparable Lenoir cycle: equivalence ratio Ø = 0.5 and γ = 1.4; state points, except state point *D*, based on stagnation values (static operation).

Comparison with Fig. 6 reveals the substantial influence of specific heat ratio γ on the results. The lower the value of γ, the lower the temperature ratios achieved and, to a lesser extent, the lower the increase in the dimensionless entropy values. The latter phenomenon is due to the increase of specific heat associated with the lower value of γ applicable to the Fig. 8 case. In the absolute sense, entropy values are greater for Fig. 8 than the corresponding entropy values applicable to Fig. 6.

For each case, the corresponding surrogate idealized constant-volume combustion, or Lenoir, cycle has been added to Figs. 5–8, inclusive for energy inputs equal to those used for the corresponding idealized PDE cycles. In each case, the constant-volume cycle realizes a slightly greater entropy increase than the corresponding idealized PDE cycle.

Table 1 presents a tabulation of the PDE cycle Mach numbers for the Ø and γ values investigated. Table 1 also presents the thermal efficiencies of the constant-volume and corresponding PDE cycles

Table 1 Mach numbers and idealized cycle efficiencies

Ø	γ	M'_X	M_Y	M_Z	η_{PDE}	η_{CV}	$\eta_{\mathrm{PDE}}/\eta_{\mathrm{CV}}$
1.0	1.4	7.197	1.7706	0.692	0.428	0.408	1.046
0.75	1.4	6.275	1.737	0.684	0.400	0.374	1.070
0.5	1.4	5.86	1.673	0.672	0.364	0.336	1.083
0.75	1.286	5.468	2.034	0.733	0.312	0.293	1.065

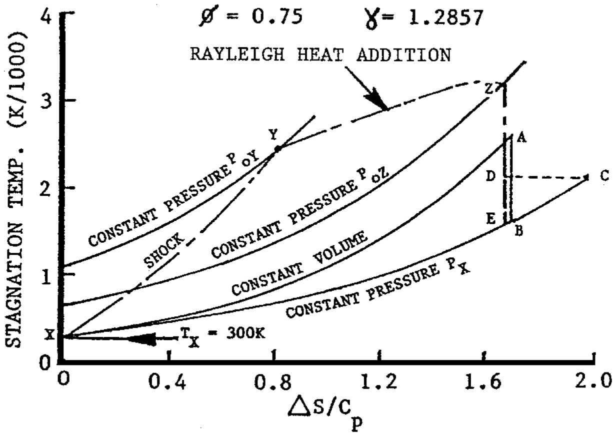


Fig. 8 Temperature–entropy diagram for idealized PDE and comparable Lenoir cycle: equivalence ratio Ø = 0.75 and γ = 1.2857; state points, except state point *D*, based on stagnation values (static operation).

and the ratio $\eta_{\mathrm{PDE}}/\eta_{\mathrm{CV}}$. The cycle efficiency can be expressed, for a Lenoir, or constant-volume, cycle as

$$\eta_{\mathrm{CV}} = \frac{\text{work done}}{\text{heat supplied}}$$

thus, invoking Eq. (27),

$$\eta_{\mathrm{CV}} = \frac{C_v(T_A - T_X) - C_p(T_B - T_X)}{C_v(T_A - T_X)}$$

Therefore,

$$\eta_{\mathrm{CV}} = 1 - \gamma\frac{(T_B - T_x)}{(T_A - T_X)} \tag{28}$$

or, where the specific energy supplied at constant volume equals that supplied to a corresponding PDE cycle, that is, the enthalpy difference between stations Y and Z with a stationary wave:

$$\eta_{\mathrm{CV}} = 1 - \frac{(T_B - T_X)}{(T'_{0Z} - T'_{0Y})} \tag{29}$$

For the PDE cycles, the efficiency η_{PDE} can be expressed as the ratio

$$\eta_{\mathrm{PDE}} = \frac{\text{heat supplied-heat rejected}}{\text{heat supplied}} \tag{30}$$

which can be reduced to a relationship the same as Eq. (29), with the exception that T_E is substituted for T_B:

$$\eta_{\mathrm{PDE}} = 1 - \frac{(T_E - T_X)}{(T'_{0Z} - T'_{0Y})} \tag{31}$$

The work done by the PDE cycles consists of that obtained by expansion from state D to state E (Figs. 5–8), plus kinetic energy obtained from the discharge of the pressure wave from the outlet end of the detonation tube. Hence, an explicit statement of the work done by a PDE cycle is much more complex than that for the constant-volume, or Lenoir, surrogate cycle. Nevertheless, the fundamental statement represented by Eqs. (30) and (31) is correct. Note that states B and E do not contain hidden kinetic energy terms because

Table 2 PDE pressure ratios

Ø	γ	P_Y/P_X	P_{0Y}/P_X	P_Z/P_X	P_{0Z}/P_X
1.0	1.4	60.4	331.7	30.3	41.7
0.75	1.4	45.8	239.3	23.3	31.8
0.5	1.4	31.2	143.2	15.9	21.6
0.75	1.286	33.5	270.8	17.2	24.0

Table 3 PDE temperature ratios

Ø	γ	T_Y/T_X	T_{0Y}/T_X	T_Z/T_X	T_{0Z}/T_X
1.0	1.4	11.03	17.95	18.09	19.83
0.75	1.4	8.61	13.80	13.89	15.19
0.5	1.4	6.18	9.64	9.62	10.49
0.75	1.286	5.17	8.22	9.95	10.72

the state points represented on the temperature–entropy planes describe stagnation conditions, with the exception of state point D. Table 2 represents, for the PDE cycles, the pressure ratios involved. Table 3 shows the corresponding temperature ratios.

Discussion

The PDE cycle expansion process (*ZD*, Figs. 5–8) cannot take place fully until some fluid has left the detonation tube. This is because the expansion waves, originating from the closed head end of the detonation tube, will generate an expansion wave, marking the completion of combustion and traveling at the local speed of sound plus the local gas velocity. This wave keeps pace with, but lags slightly downstream of, the detonation wave shock front. However, the expansion process is ideally isentropic and, hence, can be drawn on the T–S plane.

For a PDE subjected to forward motion, a profitable use of an intake ramming phenomenon would be to supercharge the detonation tube during the scavenge and postscavenge portion of the cycle. This would have the effect of converting the Lenoir-type surrogate cycle to a more efficient Humphrey, or the identical and better-known Atkinson, cycle. However, to consider this possibility in depth requires that some provision be made to, in effect, close off cyclically, either mechanically or gasdynamically, the detonation tube exit. Because, as far as the author is aware, no provisions of this kind have yet been made on experimental PDE units, this possibility will not be discussed further. A general problem with the PDE concept appears to be the high, and very variable, exit pressure ratios that make exhaust-nozzle design difficult. This problem has, in the past, caused difficulties with a gas-turbine pressure-gain combustor system.[9]

It appears that the constant-volume cycle is a very acceptable, and easy to analyze, surrogate cycle for the more complex PDE concept. The efficiency advantage of the idealized PDE cycle appears to be in the region of 5%, relative to that of the surrogate cycle, for equivalence ratios approaching unity when using hydrocarbon fuels. It seems relatively unlikely that, with such fuels equivalence ratios, very much less than unity can support detonation waves in practice. When it is considered that the shock and combustion mechanisms of a PDE involve flows at high gas velocities, it seems likely that a simple constant-volume cycle may well be a very good analogy of a PDE cycle, as has been suggested previously.[10] If account is taken of the greater likelihood of dissociation in PDEs, due to the very high cycle maximum temperature, relative to constant-volume surrogate cycles, it may be that the apparent advantage of about 5% in efficiency, noted here, may well be eroded. Povinelli[11] shed some light on the significance of dissociation in PDEs.

The kinetic energy production efficiency of an idealized constant-volume cycle or an idealized PDE cycle, is relatively low, about one-half of that of an idealized high-bypass ratio turbofan cycle. This implies problems, under takeoff conditions, for a PDE-powered vehicles when intake ramming is nonexistent or negligible. Perhaps a nonsteady flow thrust augmenter may help to alleviate PDE problems at low forward speeds.[10]

A major asset of a detonation wave is the ability to ignite, very rapidly, a field of undiluted reactants. In practice, the surrogate constant-volume cycle would, no doubt, present considerable difficulties due to the relatively low flame speeds that can be expected, even with a high turbulence level, of about 30 m/s ($\sim$100 ft/s) in stoichiometric fuel/air mixtures.[12] However, nominally, constant-volume-type combustion systems have been made to operate satisfactorily, essentially as pressure-gain combustors for gas turbines.[13] These units mix the reactants with residuals of combustion from previous cycles vigorously, resulting in relatively low pressure and temperature excursions compared with those expected with PDEs. The mixing of the reactants with residual products of combustion reduces the time required for the chemical kinetics considerably and also eliminates the need to ignite each cycle by external means once startup has occurred. Furthermore, this type of device does not need to employ mechanical valves at either the inlet or exit ports.[13,14] Because of the relatively low maximum temperatures achieved, coupled with short residence time, the NO_x production also appears to be relatively low.[14]

Conclusions

The main conclusions drawn from the study are as follows:

1) The cyclic pressure and temperature ratios achieved are proportional to the equivalence ratio Ø.

2) The ratio of specific heats γ has a strong influence on the pressure and temperature ratios achieved. Comparison of the two results, both for $Ø = 0.75$, (Fig. 6, $\gamma = 1.4 = \frac{7}{5}$ and Fig. 8, $\gamma = 1.2857 = \frac{9}{7}$) confirm this observation.

3) There is very little difference, for static operation, between the idealized performances of PDE cycles and surrogate Lenoir (constant-volume combustion) cycles. The difference in efficiency between the two cycles, for a prescribed γ value, diminishes as Ø increases. The efficiency of an idealized PDE cycle exceeds that of the corresponding surrogate Lenoir cycle. The latter situation is not surprising because the equality of the thermal input of a surrogate cycle to that of the corresponding PDE is based on the decay of the PDE wave action, irreversibly, into internal energy.

4) It appears that, provided intake-charge ramming can be achieved under flight conditions, an appropriate, idealized surrogate cycle replacing the relatively inefficient Lenoir cycle would be the Humphrey, or the identical Atkinson, cycle. It can be shown that the overall affect is to improve the efficiencies of both the idealized PDE cycle and the idealized surrogate cycle, with only a small difference in efficiency between the PDE and surrogate cycles.

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