JOURNAL OF PROPULSION AND POWER
Vol. 13, No. 2, March–April 1997

Evaluation of Performance Loss Methods for High-Speed Engines and Engine Components

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A comparative study of high-speed engine performance assessment techniques based on exergy (available work) and thrust potential (thrust availability) is summarized. Simple one-dimensional flowfields utilizing Rayleigh heat addition and friction are used to demonstrate the inability of conventional exergy techniques to predict engine component performance, aid in component design, or accurately assess flow losses. The thrust-based method yields useful information in all of these categories for these flows. The conventional definition of exergy includes work that is inherently unavailable to an aerospace Brayton engine. An engine-based exergy is developed that accurately accounts for this inherently unavailable work; performance parameters based on this quantity yield design and loss information identical to the thrust-based method.

Nomenclature

A	=	cross-sectional area, m^2
C_f	=	skin friction coefficient
Ex	=	exergy or available work per mass, J/kg
FW	=	thrust work per mass, J/kg
L_{opt}	=	optimal combustor length, m
M	=	Mach number
$\dot{m}$	=	mass flow rate, kg/s
P	=	pressure, N/m^2
R	=	gas constant, J/kg K
s	=	entropy per mass, J/kg K
T	=	temperature, K
u, U	=	velocity, m/s
ΔQ	=	heat interaction per mass, J/kg
$\eta_c(x)$	=	combustion efficiency analog for Rayleigh heat addition
$\eta_{ee}(x)$	=	engine thrust effectiveness
$\psi(x)$	=	rational efficiency, exergy-based

Subscripts

E	=	exit condition of actual engine, fixed area
Ei	=	exit condition of ideal engine, reversible and complete heat release, fixed area
Ei (no heat)	=	exit condition of reversible engine, no heat added, fixed area
Eng	=	engine-based
ER	=	exit condition of reversible engine, fixed area
expend	=	expended by vehicle
incomp	=	incomplete heat release
irr	=	irreversible
0	=	ambient conditions

Introduction

THE successful development of a high-speed airbreathing engine requires the thorough optimization of the propulsion system and its components. This optimization process should be done with respect to the vehicle in which the engine is embedded, just as the vehicle itself should be optimized for the projected mission it is to perform. Ideally, for any speed regime, an aerospace engine (and each individual engine component) should be designed within the overall vehicle design effort to ensure true optimization; this would lead to a specific engine for a specific vehicle. This procedure usually has not been done because of issues of increased cost and complexity. Aerospace engine selection has traditionally been made in vehicle design efforts by examining candidate engine parameters such as specific thrust and specific fuel consumption and ensuring that the proposed engine meets installed thrust requirements while minimizing the onboard fuel necessary over the duration of the mission. The designer, after analysis of candidate engine characteristics, can generally attach the engine to the airframe without extensive integration and still satisfactorily achieve the mission objectives for lower-speed systems. For high-speed vehicles, however, which have inherently thin performance margins, the fundamental integration of the engine and the vehicle are of utmost importance; engine design and engine component design should be done within the context of the vehicle design process itself. Therefore, it is not advisable in high-speed engine analysis to attempt to separate engine (or engine component) performance assessment from the vehicle.

In the context of high-speed propulsion, if the question is asked whether engine A or engine B is better, then the answer depends very much on the vehicle(s) with which A and B are integrated. In that respect, the matter of ranking different engines becomes inseparable from the question of ranking different vehicles. A further problem with this particular question is that high-speed engine performance is much less scalable with engine size than low-speed engine performance (i.e., one might roughly estimate that doubling the cross-sectional area of a turbojet would double the delivered thrust and fuel consumption; for high-speed flight, however, where scale effects can be significant, such an approximation may be completely erroneous). More reasonable questions for high-speed propulsion system analysts to ask would be the following: how well is a given engine (or engine component) performing, where are the performance losses occurring, and what flow mechanisms are responsible for the losses and to what degree? Further, how do changes in the characteristics of the engine or an engine component affect engine performance, and how are design features of an engine component to be chosen within the larger engine (or vehicle) iterative design procedure? This investigation seeks to shed light on two current methods that have been suggested for answering these and related questions. These two methods are based on 1) standard exergy (available work) concepts and 2) thrust-work-potential concepts. Neither

Received Feb. 20, 1996; revision received Aug. 5, 1996; accepted for publication Aug. 9, 1996.

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method is recent in development; exergy has been successfully used for many years for a wide variety of ground-based engineering processes, but its application to aerospace engines has been somewhat more limited.[1–7] Thrust potential[8–10] (or engine thrust effectiveness) is a modification and extension of a much older propulsive concept called the combustor effectiveness that has been in use for over 40 years.[11] This investigation uses very simple one-dimensional steady flows with Rayleigh heat addition and friction to illustrate and clarify issues relating to the thrust-potential and exergy methods (when applied to high-speed aerospace engines).

To establish the performance baseline for an aerospace propulsion system, consider an engine (such as a scramjet) operating at some given inflow conditions with some fixed amount of energy expended in the engine (corresponding to fuel used in a real engine). The engine has some real flow losses (i.e., losses in total pressure or, equivalently, entropy increases caused by irreversible mechanisms), incomplete combustion (less than 100% combustion efficiency), and some specific finite nozzle exit area. An engineer tasked with improving the performance of this engine (at these conditions) has (possibly) three ways to perform this task: 1) decrease the irreversibilities within the engine, 2) increase heat release (increase the combustion efficiency), and 3) increase the nozzle exit area. These three routes are coupled, i.e., increasing heat release by modifying the combustor may result in greater total pressure losses (more irreversibilities), or increasing nozzle exit area may increase the irreversibilities through greater friction, etc. Nature provides absolute limits for the first two of these methods:

1) The flow cannot be more reversible than that of the completely reversible engine, i.e., the engine that has no total pressure losses or, equivalently, no irreversible entropy increases.

2) The maximum possible released heat into the flow is equal to the externally provided heat input (complete combustion). Further, the nozzle exit degree-of-expansion is limited (constrained) by the external aerodynamic drag. These three criteria (degree of irreversibility, degree of heat release, and degree of expansion) are critical in assessing the actual performance of the engine for some given inflow conditions and heat input.

Both exergy and thrust-work potential are based on work availability concepts, i.e., both describe work that is potentially available as measured from a reference condition. Parameters based on either of the methods decrease in a flow because of irreversibilities and increase with heat (energy) addition. Such behavior is necessary if a parameter is to be used for comprehensive engine (or engine component) design. This can be illustrated by considering two simple scramjet combustors, both with total pressure losses and scheduled heat releases; one combustor with greater total pressure losses may have associated greater heat release such that it is a better performer than the other combustor, which has less total pressure loss, but less heat release. Obviously, a comprehensive performance parameter must be able to distinguish such a tradeoff; both exergy and thrust-work-potential have this ability. In contrast, combustion efficiency and the total pressure ratio are performance parameters which, while useful and informative, are not comprehensive in nature.

Exergy at an engine station is defined as the maximum reversible work that can be obtained from the flow as measured from the reference (usually ambient) conditions. Losses in exergy are, by definition, directly proportional to irreversible entropy gains; exergy losses in individual components caused by specific irreversible mechanisms (as well as Carnot losses) can be readily assessed. In addition, exergy loss caused by incomplete heat addition can be easily computed, at least for the simple flowfields examined here. The rational efficiency of an engine component is defined as the ratio of the exergy exiting the component to the total exergy entering the component.[4,5] This implies, for both physical and mathematical consistency, that the rational efficiency of the overall engine is the ratio of exergy exiting the engine to the exergy entering the engine (through both air and fuel). However, since the thrust work is the truly useful work of the engine (rather than the exergy), Murthy and others[3–5] define a true rational efficiency of the overall engine described as the ratio of engine thrust work to exergy entering the engine. Nevertheless, component performance and losses within the engine are computed using the original exergy-based rational efficiency (exergy out over exergy in). This inconsistency between how performance and losses are measured for the overall engine (in terms of thrust) and how performance and losses are measured for an individual component within the engine (in terms of exergy) violates the fundamental principle that, to be useful, a comprehensive performance parameter must be consistent in form whether applied over an engine component or over the entire engine. Such consistency is necessary because the segmentation of a high-speed engine into components is an arbitrary process from the standpoint of performance assessment, i.e., the beginning of the nozzle can be viewed equally as a downstream extension of the combustor; there is no fluid-dynamic distinction between the two components. In fact, the entire engine can and should be viewed as a single entity for performance assessment; such a perspective will always result in a superior overall engine design. Thus, each component in the engine, however identified, should ultimately be assessed in terms of how well it contributes to the achievement of the overall purpose of the engine. This mandates a synergistic component design process.

The concept of thrust-work potential is based on the preceding discussion and the observation that the main purpose of an aerospace engine is to provide adequate thrust to meet mission cruise and acceleration requirements. This leads naturally to the concept of characterizing the local performance of flow in terms of its ability to produce engine thrust. On an engine level, this idea is rooted in the basic concept of the overall engine efficiency.[12] Note that Curran and Craig[13] presented the results of an investigation that suggested the general application of engine-based stream-thrust assessment for individual component design. This article and related papers[8–10] represent, in many respects, a continuation in the direction first established by Curran and Craig.[13] Thrust-work potential is most usefully defined as the overall vehicle net thrust-work obtainable if the flow at the station of interest is expanded isentropically to the exit area of the engine. Engine thrust effectiveness is here defined as the ratio of the actual engine net thrust (or local net thrust potential) to the ideal engine net thrust (assuming reversible flow and complete combustion).[9]

The next section of this paper presents a simple combustor design problem utilizing both exergy and thrust-potential methods in which both methods are tasked with optimizing a single design parameter. The effect of nozzle expansion on the results obtained for this problem is also shown. The third section illustrates, again using simple examples, the use of exergy and thrust-potential methods for identifying component losses within a design context; the method of directly computing the thrust losses caused by irreversibilities is also discussed. The conventional exergy-based method is shown in both the second and third sections to yield less effective design information than the thrust-potential method. This is primarily because of the fact that conventional exergy does not account for the degree of nozzle expansion. Finally, the fourth section introduces the engine-based exergy that adequately accounts for the open-cycle nature of the Brayton cycle aerospace engine; this modification to the standard exergy method is shown to unify aerospace engine/component performance assessment obtained using the exergy method with performance assessment using the thrust-based method.

Component Design Comparison Using Exergy and Thrust-Based Efficiencies

To examine and contrast the exergy-based rational efficiency method and the thrust-potential-based engine effectiveness

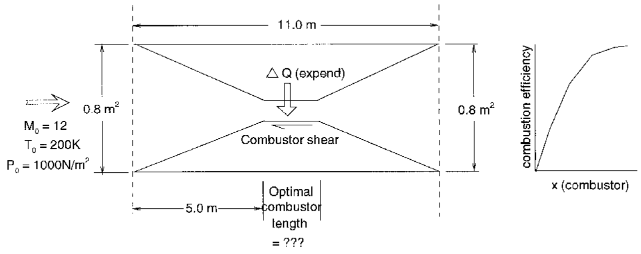

Fig. 1 Schematic of simple scramjet engine with Rayleigh heat addition and shear in combustor.

method for the design of high-speed aerospace engines and engine components, a very simple and easily duplicated design problem is posed. Any method that is to be applied to complex problems (real engines) should certainly be expected to provide useful information for simple conceptual problems. The successful method should also be expected to work no matter what the degree of design constraints on the problem, i.e., whether or not particular vehicle constraints such as overall engine length are enforced, or whether isentropic flow in a specific component is specified.

Consider a highly simplified scramjet as shown in Fig. 1. The flight Mach number M_0 is 12, the ambient temperature T_0 is equal to 200 K, and the ambient pressure P_0 is equal to 1 kPa. Let the gas flow throughout the scramjet engine be standard air with constant specific heats and steady $\dot{m}$. The inlet is isentropic with a contraction ratio of 20. Rayleigh heat addition takes place in the constant-area combustor along with relatively high skin friction. The energy expended (the energy price paid by the vehicle or the maximum heat release that could be obtained if 100% mixing and combustion occurred), is constant at $\Delta Q_{\text{expend}} = 1{,}000{,}000$ J/kg (air); however, the heat released into the flow $\Delta Q_{\text{released}}$ is scheduled such that a η_c is modeled, where

$$\eta_c = \Delta Q_{\text{released}}(x)/\Delta Q_{\text{expend}} \tag{1}$$

The combustion efficiency distribution utilizes an exponential distribution with x (as shown in Fig. 1), which approximates an actual η_c distribution in a true scramjet flowfield that has fuel injection and burning. It is emphasized that ΔQ_{expend} is fixed for all cases (i.e., the vehicle-expended energy in all cases is the same; thus, η_c as described here provides a simple analogy for modeling a fuel–air energy-based combustion efficiency in a complex flow with upstream fuel injection and mixing-limited exothermic reactions.) The axial distribution of η_c is unchanging vs axial distance for all cases. C_f in the combustor is 0.02. For the initial investigation, the nozzle is assumed to be isentropic and the nozzle exit area A_E is set equal to the inlet face area A_0 (i.e., this is imposed as a design constraint). Further, no heat release is allowed within the nozzle component for any case.

With this simple system it is apparent that there will be an L_{opt}; any combustor length greater than L_{opt} will result in a loss in performance. This is because $\Delta Q_{\text{released}}$ is asymptotic to ΔQ_{expend}; progressively smaller amounts of heat are released into the flow per unit length as the combustor lengthens. Because of ongoing friction, there is some point at which the additional heat release associated with additional combustor length is negated (in terms of performance benefit) by the friction associated with that additional combustor length. The design challenge is to find L_{opt}, the combustor length that optimizes the performance of the vehicle. This will be done by utilizing both the rational efficiency method (which is exergy-based), as described in Refs. 3–5, and the engine thrust effectiveness, which is based on the thrust-potential concept.[8–10] These parameters will be calculated as a function of distance along the combustor, over an overall 1 m combustor length.

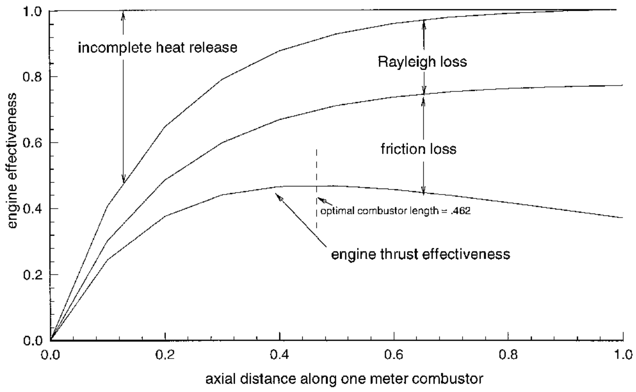

Fig. 2 Engine thrust effectiveness and losses vs axial distance along combustor.

The thrust-potential-based engine effectiveness at a station is defined as the ratio of the net engine thrust assuming an isentropic expansion process to the nozzle exit area (taken from the local station of interest) to the net ideal engine thrust, i.e., to the engine thrust obtained for reversible and complete heat addition with no friction. This parameter can be written in terms of the stream thrust $\dot{m}u + PA$ as

$$\eta_{ee}(x) = \frac{\dot{m}u_E(x) + P_E(x)A_E - (\dot{m}u_0 + P_0A_0)}{\dot{m}u_{E_{\text{ideal}}} + P_{E_{\text{ideal}}}A_E - (\dot{m}u_0 + P_0A_0)} \tag{2}$$

where, for example, $u_E(x)$ is the velocity of the local flow expanded isentropically to the nozzle exit area.

The actual thrust-potential-based engine effectiveness distribution is plotted as the lower curve in Fig. 2. It is maximized at 0.46, i.e., an optimal combustor length of 0.46 is predicted. Also shown are calculated losses in this parameter caused by irreversibilities associated with friction and heat addition at finite Mach number (Rayleigh losses) as well as the loss caused by incomplete heat release. These losses are computed by utilizing a technique[9] that can identify and quantify losses in engine thrust (or station thrust-potential) caused by coupled irreversibilities and incomplete combustion. This technique will be discussed further in the third section. The engine thrust effectiveness is seen to be maximized at the axial station where the sum of the lost thrust caused by irreversibilities and incomplete heat release is minimized. In fact, η_{ee} can be defined as

$$\eta_{ee} = \frac{FW_{\text{ideal}} - \Delta FW_{\text{irr}} - \Delta FW_{\text{incomp}}}{FW_{\text{ideal}}} \tag{3}$$

where ΔFW_{irr} is the lost thrust work caused by irreversibilities, and $\Delta FW_{\text{incomp}}$ is the lost thrust work caused by incomplete heat release.

The rational efficiency is plotted as the lower curve in Fig. 3 as a function of the axial distance along the combustor. The rational efficiency is defined in a manner consistent with Ref. 4, i.e., it is measured from the ambient conditions (T_0, S_0) at the inlet entrance (at zero velocity), or at a station x:

$$\psi(x) = \frac{\displaystyle\int_0^x \delta Q_{\text{released}} + \frac{u_0^2}{2} - \int_0^x T_0\,\mathrm{d}s}{\Delta Q_{\text{expend}} + \dfrac{u_0^2}{2}} \qquad \text{(Exergy Method)} \tag{4}$$

The rational efficiency predicts an optimal combustor length of 0.952 m, i.e., ψ (or exergy) is a maximum at this axial location in Fig. 3. This is approximately twice the optimal length predicted utilizing the thrust effectiveness. This result illustrates the fundamental difference between component de-

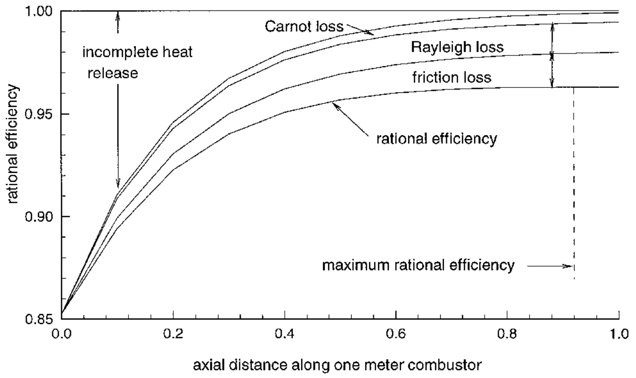

Fig. 3 Rational efficiency and losses vs axial distance along combustor.

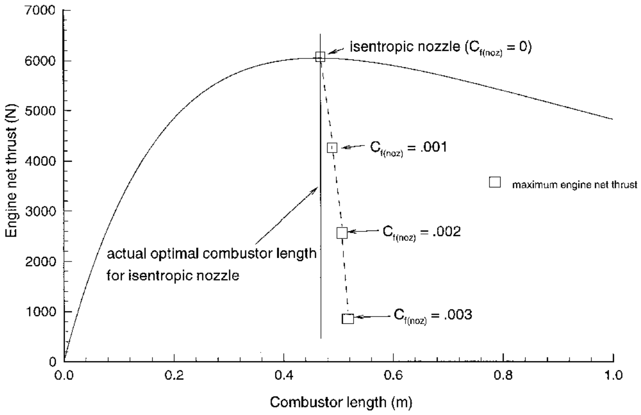

Fig. 4 Actual engine net thrust vs combustor length chosen for range of nozzle skin friction coefficients.

signs obtained utilizing the two methods, even for this highly simplified case in which a single design parameter (L_{opt}) is sought. The distribution of losses for the exergy-based rational efficiency is also shown in Fig. 3. Losses are caused by friction, Rayleigh heat addition, and incomplete heat release. There is an additional loss shown for this method that is neither a loss caused by irreversibilities nor incomplete combustion, but which is associated with the Carnot efficiency of the complete reversible cycle. Like the engine effectiveness, the rational efficiency is maximized at the axial location at which the sum of all efficiency losses is minimized. There are, however, significant differences in the loss distributions and relative percentages between the thrust-based method (Fig. 2) and the exergy-based method (Fig. 3).

Figure 4 plots actual net thrust of the engine for various actual combustor lengths. The maximum engine net thrust is obtained when a combustor length of 0.46 m is used; this corresponds exactly to the optimal length predicted using the thrust-potential method. Although this result is not surprising when the definition of thrust potential (and the associated engine thrust effectiveness) is considered, it is significantly different than the alternative optimal combustor length predicted by the exergy method. As a matter of additional interest, the effect of actual nozzle losses (modeled by increasing the skin friction coefficient in the nozzle) on both maximum net thrust delivered and the combustor length at which this maximum thrust occurs is shown by the pattern of square symbols in Fig. 4. The actual optimal length of the combustor changes marginally from 0.46 to 0.5 m for a range of actual nozzle skin friction coefficients. However, neither exergy-based nor thrust-potential-based methods account for any losses (or energy transfer) subsequent to the station of interest (although such losses may be approximated if desired by simple modifications to the methods).

Table 1 Optimal engine summary

	Thrust potential	Exergy
Combustor length	0.46 m	0.93 m
Engine net thrust	6044 N	4810 N
Heat (expended)	1 MJ/kg	1 MJ/kg
External aerodynamics	Same	Same

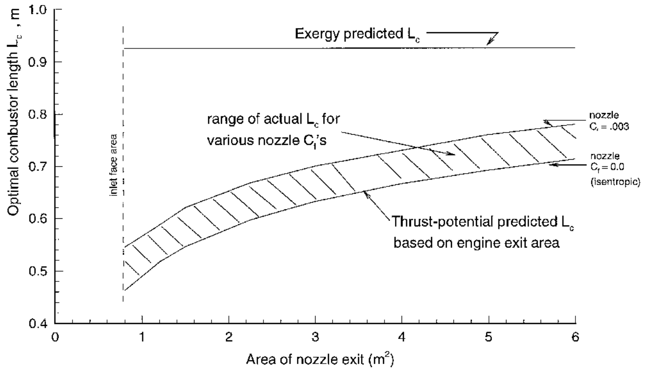

Fig. 5 Influence of degree of nozzle expansion on optimal combustor length including exergy-based and thrust-potential optimal lengths.

A summary of the two optimal combustor designs obtained by using the two methods is presented in Table 1. This summary illustrates that the exergy-based method yields an engine design that has twice the necessary combustor length and delivers significantly less thrust than the thrust-potential-based method. Both designs have the same energy cost to the vehicle (ΔQ_{expend}) and have identical external aerodynamics.

It is instructive to plot actual optimal combustor lengths for varying nozzle exit area along with the optimal combustor lengths as predicted by the thrust-potential and exergy methods. This is done in Fig. 5 for a range of nozzle skin friction coefficients. Several observations can be made by examining Fig. 5. First, the thrust-potential method utilizing the nozzle exit area provides very useful predictions across the entire range of nozzle exit areas; this prediction is, in fact, exact for $C_f = 0$. Secondly, the exergy-based method (rational efficiency) recommends an optimal combustor length that is entirely independent of the degree of expansion and is significantly greater than the true optimal. As the flow is expanded to very large nozzle exit areas, the difference between the actual optimal length (along with the thrust-potential based optimal) and the exergy-based optimal narrows somewhat. Finally, this figure illustrates in a clear and unambiguous manner the crucial fact that the degree of nozzle expansion is integral to engine/component design. By extension, the performance assessment technique used for either component or engine design should account for this degree of expansion. Each engine component should be designed, assessed, and optimized with respect to the engine.

Comparison of Component Losses Using Exergy and Thrust-Based Methods

It is important that the successful performance assessment method consistently yield accurate information regarding flow losses. The method should be able to discriminate and quantify performance losses caused by various flow irreversibilities and should identify the component or engine region in which the loss actually occurred. All reasonable exergy-based approaches relate losses in exergy to engine performance losses (in terms of engine thrust) through the introduction of some kind of overall engine effectiveness parameter or by measured reductions in overall engine propulsive efficiency. However, these methods assess component performance losses in terms of the exergy losses that occur within a particular component. This section reviews and demonstrates (using very simple examples) the direct analytical link between thrust losses and irreversibilities. The method has the ability to identify (at a given engine station) the particular upstream component or engine region with which a thrust loss caused by a particular loss mechanism is associated. This method works either in terms of thrust potential or in terms of loss in raw stream thrust at a given station. In addition, the inability of exergy methods (without suitable modification) to accurately assess this same information is demonstrated.

First, consider an extremely simple one-dimensional flow through a 10-m-long constant-area adiabatic duct with friction ($C_f = 0.002$) as shown in Fig. 6. Let the inflow conditions be $U_0 = 2000$ m/s, $T_0 = 620$ K, and $P_0 = 1000$ N/m^2. Assume standard air with constant properties. This flow has only one possible propulsively useful performance descriptor: drag (or stream thrust loss caused by friction). There are both measurable exergy losses as well as stream thrust losses as measured from the duct inflow values. Let the duct be arbitrarily sectioned at the 3.333-m location (one-third of the way along the duct axis, at point b), and call the upstream component Y, and the downstream component Z. The component Y has some quantifiable irreversible entropy increase (per unit mass), $\Delta s_y = 281$ J/kg K. Likewise, Z has some different quantifiable irreversible entropy increase, $\Delta s_z = 271$ J/kg K. Using the one-dimensional flow equations, the stream thrust at b is calculated as 885 N, whereas the stream thrust at the end of the duct E is calculated as 797 N. This indicates a stream thrust loss (or drag) of 50.6 N for component Y and 88 N for component Z. Note that component Z has a far greater stream thrust loss relative to its entropy gain than component Y.

The calculation of the exergy losses (based on the inflow temperature and entropy) is given as $\Delta Ex_{\mathrm{loss}} = T_0(\Delta s_y + \Delta s_z)$, where Δs is the change in entropy per mass. Hence, $\Delta Ex_y = 174{,}220$ J/kg and $\Delta Ex_z = 168{,}020$ J/kg. These component exergy losses are then simply proportional to the particular component entropy gain, and do not yield the performance information, noted previously, that the Z component (the downstream component) has a much greater performance loss than component Y (the upstream component), relative to its entropy gain.

To calculate the lost stream thrust utilizing the method developed in detail in Ref. 9, the exit flow of the duct can be expanded isentropically, utilizing the relation

$$A_E(\text{expanded})/A_E = e^{\Delta s/R} \tag{5}$$

The expansion is performed by sequentially utilizing the entropy increases from the downstream component to the upstream component (this process and its thermodynamic basis are explained in Ref. 9). This process yields the exit stream thrusts for increasingly reversible flowfields (with irreversibilities removed from back to front) as measured from the actual flow. When this method is applied to a complex engine flow with coupled flow losses, it is necessary to have a complete differential description of the entropy distribution throughout the engine. However, by using this method, an extremely powerful depiction of both magnitude and engine location of the specific thrust losses caused by specific irreversible mechanisms can be made. It is important to understand that this method of expanding the actual flow to recover (and measure) thrust losses is independent of the thrust-potential method. The two methods are distinct; care should be taken that they not be confused. Unfortunately, such confusion is possible because both techniques rely on isentropic expansion processes. Computing the thrust potential of the flow at the engine station of interest requires an isentropic expansion to the exit area associated with the vehicle. Computing the thrust losses caused by upstream irreversibilities as described in Ref. 9 also requires an isentropic expansion; if this expansion is directly taken from the cross-sectional area at the station of interest, the lost thrust method actually yields the lost stream thrust at the station. The two methods can be combined by applying the lost thrust method after a thrust-potential expansion. This combination of the two techniques then yields lost thrust potential.

For the simple one-dimensional duct with friction described earlier, this method, when suitably applied using the component entropy increases, should simply return the stream thrust at b when the lost stream thrust (drag) of component Z is calculated by an initial expansion of the exit flow, and then return the stream thrust at the duct inflow when the lost stream thrust of component Y is further calculated from another subsequent expansion. Indeed, lost thrust in component Y utilizing this method is computed as 50.6 N; lost stream thrust in component Z utilizing this method is 88 N. These thrust losses are found, knowing only the state of the flow at the duct exit, the individual component entropy increases, and the order in which the irreversibilities occurred.

The lost-thrust method described here exactly and directly predicts the stream thrust loss caused by various irreversibilities within individual components and allows the rigorous identification and ranking of components in which propulsive losses occur. On the other hand, exergy does not correctly rank components and yields no useful propulsive information. Exergy losses simply scale directly with entropy losses, whereas stream thrust losses, thrust-potential losses, and engine thrust losses associated with irreversibilities within a component are not linearly scaled by the entropy increases associated with that component. In addition, exergy does not account for the effect of expansion on engine performance; Fig. 7 shows the stream thrusts for expansion processes vs nozzle exit area; the top curve is the (expanded) stream thrust for an isentropic duct, and the bottom curve is the (expanded) stream thrust for the actual duct with losses. The region between these two curves is divided into thrust losses associated with components Y and Z. These losses are computed (after the flow is first expanded to the nozzle exit area) by using the technique discussed earlier for quantifying lost component thrust. The influence of the

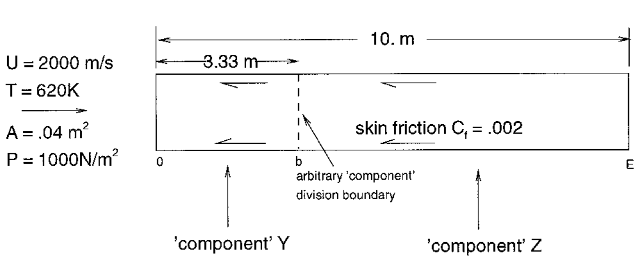

Fig. 6 One-dimensional duct with friction showing arbitrary component division boundary.

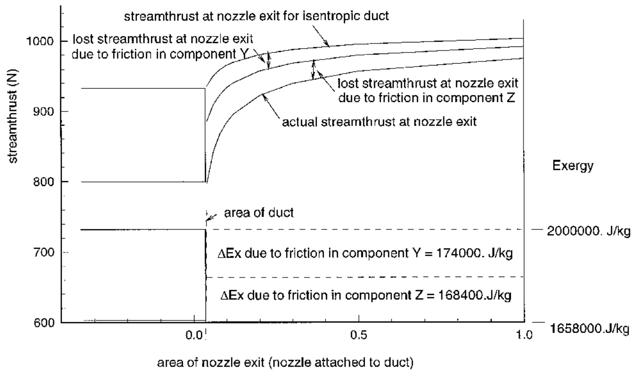

Fig. 7 Influence of degree of expansion on nozzle stream thrust obtained after one-dimensional duct with friction; showing lost thrust associated with components (bottom, exergy losses associated with components).

Table 2 Summary of engine shown in Fig. 1[a]

Irreversible mechanism[b]	Lost thrust, N	Entropy gain, J/kg K	Lost exergy, J/kg
Friction: Y	2259	349	69,800
Friction: Z	2582	226	45,200
Rayleigh: Y	2858	467	93,400
Rayleigh: Z	362	31	6200

[a]Engine net thrust = 4727 N, ΔS_{Rev} = 155 J/kg K.
[b]Combustor arbitrarily divided into components Y and Z, 1 m combustor length.

Table 3 Optimal engine summary (component-optimized)

	Thrust potential	Exergy
Engine net thrust	7555 N	6001 N
Heat expended	1 MJ/kg	1 MJ/kg
Engine geometry	Same	Same
External aerodynamics	Same	Same

losses is seen to diminish as the degree of expansion is increased. At infinite expansion, there is no measurable lost thrust caused by irreversibilities. As shown in Fig. 7, exergy methods do not account for the effect of the degree of expansion of an engine on losses. The exergy loss associated with each component is completely independent of the degree of the nozzle expansion process.

To further illustrate the issues involved with assessing component performance losses (and directing component optimization efforts), the simple scramjet problem analyzed in the previous section is revisited. This problem originally sought the optimal length of the combustor as the desired design feature; in this section, the combustor length is fixed at 1 m and the combustor is arbitrarily divided into two separate components, Y and Z, in a manner similar to the previous one-dimensional duct with friction. Both the exergy method and the thrust-potential method are then used to determine the losses caused by irreversibilities within these two components. The two (coupled) loss mechanisms in this flow are associated with heat addition at finite Mach number (Rayleigh losses) and skin friction. The particular design problem posed is as follows: identify the component in which the greatest frictional losses occur, then optimize that component (in terms of friction) by eliminating skin friction within that component (setting C_f = 0). This procedure is done using both methods, and the resulting optimized engines are compared in terms of overall performance. A summary of the diagnosis of the given engine (with 1 m combustor length and C_f = 0.02 in the combustor) is given in Table 2.

The exergy loss caused by friction is greatest in component Y; therefore, based on this method, component Y must be selected for loss reduction. The thrust loss caused by friction is greatest in component Z; based on the thrust-potential method, component Z must be selected for loss reduction. The engine is improved by eliminating skin friction within the identified component. Table 3 provides a summary of the resulting engines. Clearly, the thrust-potential method in conjunction with the lost-thrust method provides accurate information in terms of identifying component losses for aerospace engine applications.

The effect of increasing the actual nozzle exit area on the thrust losses caused by individual loss mechanisms is shown in Fig. 8, which plots the overall engine efficiency (i.e., ratio of the actual net thrust to the energy expended) and the various losses in the overall engine efficiency caused by various irreversibilities for a range of nozzle exit areas. The effect of the irreversibilities on the delivered net thrust of the engine diminishes as the degree of nozzle expansion is increased. (Note that the exergy losses are independent of the degree of nozzle expansion, as discussed earlier.) The top curve corresponds to the ideal engine with the given nozzle exit area, whereas the bottom curve corresponds to the overall efficiency of the actual engine at the same exit area. The losses resulting from individual mechanisms are quantified using the technique discussed earlier, in which lost thrust is directly related to increases in irreversible entropy.

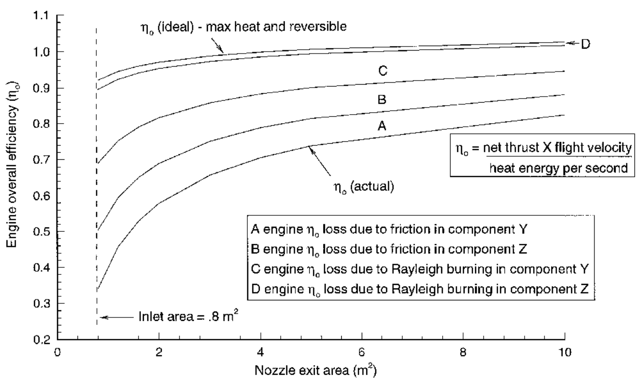

Fig. 8 Overall engine efficiency and component and mechanism losses vs nozzle degree-of-expansion.

The thermodynamic basis of conventional exergy and its relationship to engine thrust production are discussed elsewhere in detail.[14] It is shown that when a system (or component) is optimized based on conventionally defined exergy, the optimization takes place based on the assumption of cycle closure. Such an optimization would be superior (in terms of maximizing Pdv work) if the wake of the engine was suitably processed (with an isentropic expansion to T_0 and a heat-exchange device, etc.) and returned to the inlet face. An aerospace engine, however, is inevitably an open-cycle device and exhausts at a temperature generally much higher than the ambient temperature. This is true for the reversible engine with complete heat-release as well as the actual engine. Hence, the reason becomes evident for the initial prediction of a large optimal combustor length when using the exergy method in the original example in this investigation. Exergy implicitly assumes an isentropic expansion to the ambient temperature, hence, the effect of the irreversible losses is considerably lessened from that for an expansion that is based on the true engine exit area. Since the losses have less impact at low temperatures, the combustor is allowed to be longer to take advantage of additional heat release.

Engine-Based Exergy Analysis

Available work (exergy) can be readily used for the analysis of aerospace engines, providing it is suitably redefined to account for the open-cycle nature of such engines. This section describes the development of an engine-based exergy approach that enables unification of thrust- and exergy-based performance assessments. The following discussion is similar to the analysis presented in Ref. 9 in which the thermodynamic background of the methodology of identifying and quantifying thrust losses caused by irreversibilities is originally developed. Any consistent evaluation of engine performance requires the definition of the completely reversible engine to establish the performance baseline for losses in engine performance caused by irreversibilities. In addition, the ideal engine, which is both reversible and has complete heat addition, must be defined to measure performance loss caused by incomplete combustion. Under the previous assumptions of Rayleigh heat addition and one-dimensional flow, the net specific thrust of the actual engine is determined solely by the inflow conditions P_0, T_0, M_0, ΔQ, Δs_{irr}, and the degree of expansion of the nozzle A_E/A_0. The exergy (conventionally defined) is a function of the same variables, with the exception that it is entirely independent of

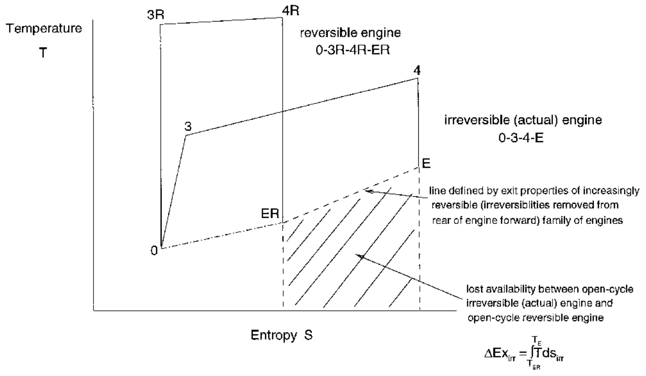

Fig. 9 Temperature–entropy diagrams for actual and reversible engines showing lost availability between the two engines.

the degree of expansion (no A_E/A_0 dependence). This fact makes exergy as usually defined (and exergy losses) unsuitable for engine design or engine component design (as demonstrated in the simple examples in previous sections). To understand how the conventional definition of exergy should be modified to account for the open-cycle nature of aerospace engines, it is instructive to examine a T–S diagram for a scramjet engine (Fig. 9). Both actual (irreversible) and reversible T–S paths for the engine with ΔQ and given nozzle exit area are shown in this figure. The path 0–$3R$–$4R$–ER describes the reversible engine; 0–3–4–E describes the actual engine. The exit pressure $P_E \neq P_{\mathrm{ER}} \neq P_0$ for a given nozzle exit area, nor does heat addition generally occur at constant pressure (or constant area) in realistic scramjet engines. Although such assumptions are often made in engine analysis, the concepts described in this and related investigations are completely general.

In Fig. 9, a family of engines with differential irreversibilities removed from nozzle exit to inlet face (all with the same nozzle exit area) defines the integration line E–ER. This line is the locus of nozzle exit temperature and entropy for this particular family of engines. Lost work between the completely reversible and the irreversible (actual) engine can be integrated over this locus line as

$$\Delta Ex_{\mathrm{irr}} = \int_{\mathrm{ER}}^{E} T \,\mathrm{d}s_{\mathrm{irr}} \tag{6}$$

This is shown as the hatched area in Fig. 9. The differential lost work increment $(T_{\mathrm{exhaust}} - T_0)\,\mathrm{d}s$ above the usual differential unavailability term $T_0\,\mathrm{d}s$, represents additional (and inevitable) unavailability, and occurs because the actual engine (as well as the reversible engine and any intermediate engine) exhausts at a temperature well above T_0. This unavailability must be accounted for in engine analysis. This equation for the lost work is closely related to the expression given in Ref. 9 for the thrust work lost caused by irreversibilities:

$$\Delta FW_{\mathrm{irr}} = \int_{\mathrm{ER}}^{E} \frac{u_0 T \,\mathrm{d}s_{\mathrm{irr}}}{u} \tag{7}$$

The integration path E–ER is identical in both expressions and the key concept of recovering work is the same; the lost work must always be recovered from the downstream location to the upstream location through the engine. Straightforward application of this method of recovering lost work utilizing either exergy [Eq. (6)] or thrust work [Eq. (7)] allows accurate analysis of flows with coupled losses and separation of losses into contributions associated with various engine components and specific loss mechanisms.

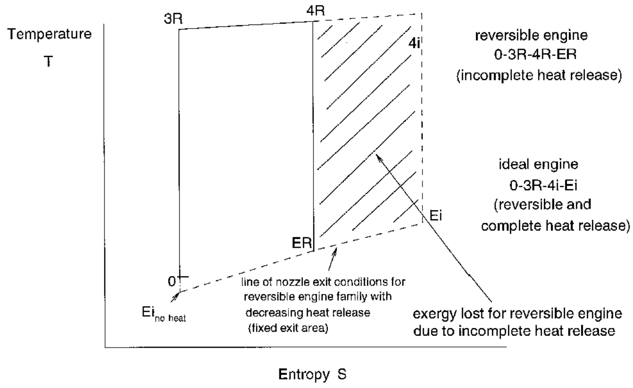

Fig. 10 Temperature–entropy diagrams for reversible engine with complete heat addition and with incomplete heat addition showing lost availability between two engines.

The lost engine-based exergy associated with incomplete combustion can be illustrated by examining the T–S diagram (Fig. 10) for the reversible scramjet with and without complete heat release. The line corresponding to nozzle exit conditions for the reversible engine family with variable heat release is indicated in this figure. Because of the nozzle exit area generally being different from the inlet area, this line truncates at Ei (no heat), which corresponds to the reversible engine with no heat release. The engine-based exergy lost caused by incomplete heat release is indicated by the hatched area in this figure and is defined as

$$\Delta Ex_{\mathrm{incomp}} = (\Delta Q_{\mathrm{expend}} - \Delta Q) - \int_{\mathrm{ER}}^{\mathrm{Ei}} T \,\mathrm{d}s \tag{8}$$

where $\Delta Q_{\mathrm{expend}}$ is the maximum heat (added) or energy expended and ΔQ is the actual heat added. Furthermore, the engine-based exergy of the ideal engine is given as

$$Ex_{\mathrm{ideal}} = \Delta Q_{\mathrm{expend}} - \int_{\mathrm{Ei(no\ heat)}}^{\mathrm{Ei}} T \,\mathrm{d}s \tag{9}$$

Based on this analysis, the actual engine-based exergy is then defined as

$$Ex_{\mathrm{Eng}} = C_p(T_E - T_0) + \frac{u_E^2}{2} - \frac{u_0^2}{2} - \int_{\mathrm{Ei(no\ heat)}}^{E} T \,\mathrm{d}s \tag{10}$$

where the integration path from Ei (no heat)–E follows the line from Ei (no heat)–ER–E (all at fixed exit area) shown in Figs. 9 and 10. The portion Ei (no heat)–ER is the locus line of exit conditions for a family of reversible engines with progressively increasing heat release, whereas ER–E is the locus line of the exit conditions for the family of engines with the same (actual) heat release, but with irreversibilities progressively removed from downstream (nozzle exit) to upstream (inlet face), as discussed earlier. This definition of exergy is entirely dependent on the degree of expansion of the nozzle, unlike the conventional definition of exergy. The true engine-based available work [Eq. (10)] can be compared to the conventional available work given here as

$$Ex_{\mathrm{conventional}} = C_p(T_E - T_0) + \frac{u_E^2}{2} - \frac{u_0^2}{2} - T_0(s_E - s_0) \tag{11}$$

The engine-based exergy leads to a natural figure-of-merit for describing the performance of an engine (or the performance potential of the flow at a particular engine station). This figure-of-merit is called here the engine-based rational efficiency; for evaluation of this quantity at an intermediate engine station,

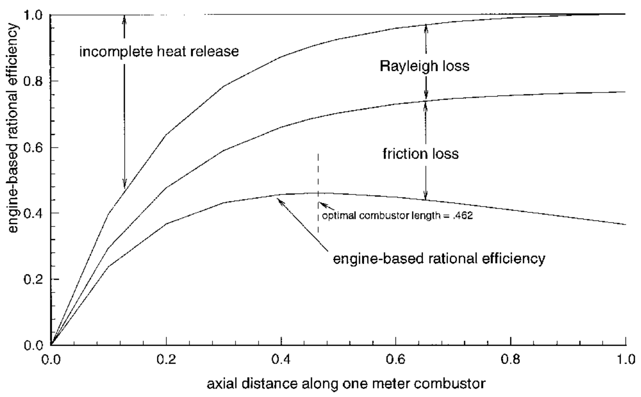

Fig. 11 Engine-based rational efficiency and losses vs axial distance along combustor for simple scramjet with optimal length predicted the same as for the thrust-potential method (compare to Fig. 2).

an isentropic expansion to the locus line ER – E is implied with subsequent recovery of lost work caused by irreversibilities located upstream of the station followed by the recovery of engine-based exergy because of incomplete combustion at that station. An engine-based rational efficiency can be defined in the following manner:

$$\psi_{\mathrm{Eng}} = \frac{Ex_{\mathrm{Eng}}}{Ex_{\mathrm{ideal}}} = \frac{Ex_{\mathrm{ideal}} - \Delta Ex_{\mathrm{irr}} - \Delta Ex_{\mathrm{incomp}}}{Ex_{\mathrm{ideal}}} \tag{12}$$

This parameter is similar in form to the engine thrust effectiveness [Eq. (4)]; in fact, the two figures-of-merit yield identical results when analyzing the simple engine flows described in this investigation. This can be seen in Fig. 11, in which the engine-based rational efficiency is plotted vs combustor length for the original example used in this investigation. The optimal combustor length is predicted as 0.46 and the lost engine-based exergy distributions caused by friction, Rayleigh losses, and incomplete heat release are indistinguishable from those shown for the thrust-based engine effectiveness (see Fig. 2). In summary, the parameters ψ_{Eng} and η_{ee} are both equally representative of engine and component performance and correctly include the effects of the degree of nozzle expansion on performance losses.

Summary

This investigation provides a basic comparison of two different methods used for assessing high-speed engine and engine component performance and losses. These methods are the exergy (or available work) method and the thrust-potential method along with their related efficiencies (the rational efficiency and the engine thrust effectiveness, respectively). The comparison between these techniques is done by utilizing very elementary and easily duplicated examples that are purposely cast in terms of engine design problems. By emphasizing extreme simplicity in these examples (Rayleigh heat addition, one-dimensional flow, etc.), fundamental and significant differences in design information that are provided by the two methods are not obscured by complicating issues that can arise in real engine flowfields. Any method proposed for evaluation of complex engine flows with real design constraints must work for exceedingly simple model flows and constraints.

The first example presented in this paper entails the selection of the optimal length for a scramjet combustor that has scheduled heat release and concurrent friction. The thrust-potential method yields accurate design information; combustor (component) design characteristics and losses are shown to be strongly dependent on the engine degree of expansion. The conventional exergy method is independent of the degree of expansion and predicts an optimal combustor length that is about twice the true optimal and results in an engine design with significantly less thrust. The second example analyzes flow in a one-dimensional duct with friction in which the duct is arbitrarily sectioned into components. This flowfield has only fluid dynamic drag as a useful propulsive descriptor of flow performance. The sectional drags do not scale directly on entropy (although exergy loss does). In fact, the maximum drag occurs in the component in which the exergy loss is the minimum. The method of directly quantifying lost thrust caused by flow irreversibilities is then reviewed; this method allows both the assessment of where and how much thrust is lost within a flowfield caused by specific upstream flow loss mechanisms. Again, the influence of the degree of expansion downstream of flow irreversibilities on performance losses is shown to be significant. The third and last example returns to the same engine flow examined in the first example and demonstrates the inability of the conventional exergy method to correctly identify the component (or flow region) that has the largest true performance loss caused by a particular loss mechanism.

The proper application of exergy-based techniques in the analysis of propulsive devices is fundamentally sound in terms of identifying thermodynamic losses. However, the conventional exergy definition includes nonengine wake processes; analytically and physically it is a closed-cycle quantity that does not account for the open-cycle nature of a jet engine. As a result, it underpredicts the effect of losses and fails to correctly identify the engine location with which the losses are associated. The last section in this article introduces and develops an engine-based exergy (available work), which is directly related to the open-cycle nature of the engine; this engine-based exergy is corrected for work that is inevitably unavailable to the engine. This lost work is a result of the fact that the engine nozzle exhausts at a temperature above the ambient. When the engine-based exergy method is applied to the original design example used in this investigation, the results are identical with the results obtained using the thrust-based method. This investigation unifies the thrust- and exergy-based methods and should satisfactorily address longstanding concerns about the use of exergy methods for the analysis of aerospace engines.

Acknowledgments

This work was performed under Grant NAG1-1189 from the Hypersonic Vehicles Office at NASA Langley Research Center. Special thanks go to Chuck McClinton for his continual support and encouragement.

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