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High-Speed Engine/Component Performance Assessment Using Exergy and Thrust-Based Methods

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HIGH-SPEED ENGINE/COMPONENT PERFORMANCE ASSESSMENT USING EXERGY AND THRUST-BASED METHODS

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Nomenclature

C_p	specific heat (constant pressure) (J/kgK)
γ	ratio of specific heats
η_c	'combustion' efficiency; controls heat release
$\Delta Q_{released}$	heat released into flow (J/kg)
ΔQ_{expend}	total heat energy expended by vehicle (J/kg)
L_{opt}	optimal combustor length (m)
ψ	rational efficiency
ψ_E	engine-based rational efficiency
T	static temperature (K)
S	entropy (J/kgK)
η_{ee}	engine thrust effectiveness
$\dot{m}$	mass flow rate through engine (kg/sec)
P	static pressure (N/m^2)
A	cross-sectional area
u or U	velocity (m/s)
irr	irreversible (subscript)
incomp	incomplete heat release (subscript)
ideal	ideal condition (subscript)
o	inlet face or flight/ambient condition (subscript)
e/E	nozzle or expansion exit condition (subscript or identifier)
C_f	skin friction coefficient
Ex	exergy (available work) (J/kg)
R	gas constant (J/kgK)
ν	specific volume (m^3/kg)
vis or viscous	frictional component
$R_{viscous}$	viscous frictional force (N)
F	thrust (N)
FW	thrust work (per kilogram) (J/kg)

FWP	thrust work potential
R	reversible (subscript)

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I. Introduction

The successful development of high-speed airbreathing engines 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 in order to ensure true optimization; this would lead to a specific engine for a specific vehicle. This procedure usually has not been done due to 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 on-board fuel necessary over the duration of the mission. The designer, after careful consideration and 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) (and the mission) with which A and B are integrated with and with which they were (hopefully) designed in conjunction with. In that respect, the matter of 'ranking' different engines becomes inseparable from the question of ranking different vehicles - which, in the final analysis, will most likely be based on technical feasibility and overall life-cycle cost. 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 which have been suggested for answering these and related questions. These two methods are based on i) standard exergy (available work) concepts and ii) thrust-work-potential concepts. Neither method is recent in development; exergy has been successfully used for many years for a wide variety of ground-based engineering processes; application to aerospace engines have 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 which has been in use for at least thirty years. This investigation uses very simple one-dimensional steady flows with Rayleigh heat addition and friction in order to illustrate and clarify issues relating to the thrust-potential and exergy methods (when applied to high-speed aerospace engines).

In order to establish the performance base-line for an aerospace propulsion system, consider an engine (such as a scramjet) operating at some given inflow conditions with some fixed amount of heat 'spent' 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 due to 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; i) decrease the irreversibilities within the engine, ii) increase heat release (increase the combustion efficiency), and iii) increase the nozzle exit area. These three routes are coupled - for instance, 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 theoretical 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 which has no total pressure losses or, equivalently, no irreversible entropy increases, and 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. Although the latter limit is somewhat different in character than the first two limits, it will be seen to be an important constraint when assessing engine or component performance and component design characteristics. It can be argued that, in the absence of external information or weight issues, the nozzle degree-of-expansion is unlimited (theoretically) by nature such that an infinite expansion of the nozzle is the natural limit, at least from the engine-alone standpoint. In any event, these three criteria (degree of irreversibility, degree of incompleteness 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 system work which is potentially available as measured from some set of reference conditions. Parameters based on either of the methods can be shown to decrease in a flow due to irreversibilities and to increase with heat (energy) addition. This behavior is necessary if a performance parameter is to be used for meaningful and 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 trade-off; 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 usually defined as the maximum reversible work which can be obtained from the flow as measured from the reference (usually ambient) conditions. It is a closed-cycle quantity which accounts for the effect of losses and heat release upstream of the station of interest at which it is calculated. Losses in exergy are, by definition, directly proportional to irreversible entropy gains; exergy losses in individual components due to specific irreversible mechanisms (as well as Carnot losses) can be readily assessed. In addition, exergy loss due to incomplete heat addition can be easily computed, at least for the flow-fields examined here which have simple Rayleigh heat addition.

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), references [3]-[5] define a 'true rational efficiency' of the overall engine. This is described as the ratio of the engine thrust work to the 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 a useful and 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. For example, 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. In this sense, 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.

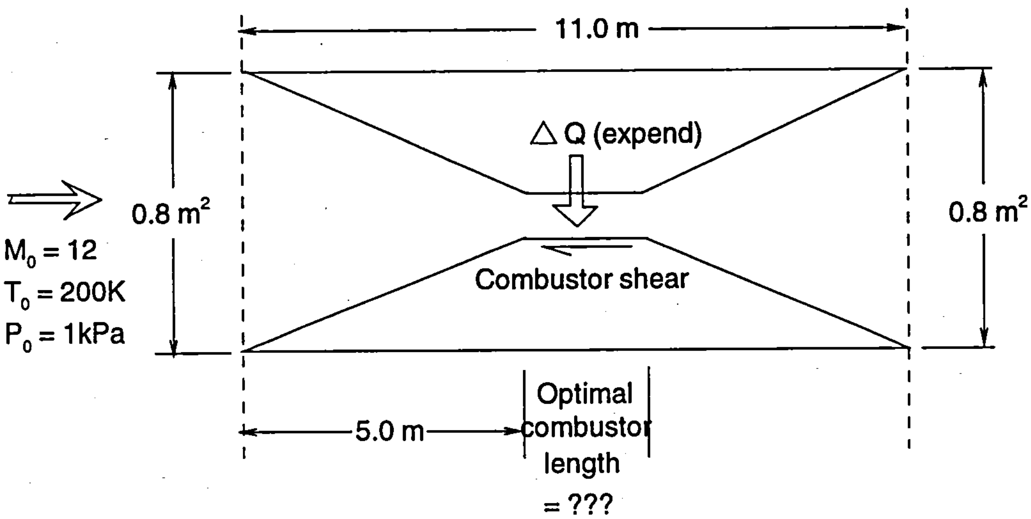
The concept of thrust-work potential is based on the preceding discussion and the observation that the main purpose of an aerospace engine is to provide adequate thrust in order to meet mission cruise and acceleration requirements. The amount of fuel that the engine consumes during the mission should be minimized in order to minimize vehicle volume (and take-off weight). Furthermore, the engine must provide adequate thrust to overcome drag (which is related back to the overall vehicle volume). This mutual dependency of engine and vehicle characteristics illustrates the mandatory integration of the vehicle-engine design process and the need for a performance parameter which can reflect this dependence. In addition, it is vital that meaningful engine design and evaluation techniques utilizing such a parameter be able to assess the performance of the individual engine components as well as the engine itself. These requirements lead 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 [11]. It should be noted that Curran and Craig in 1973 presented the results of an investigation [12] which suggested the general application of engine-based streamthrust assessment for individual component design. The present paper and related papers [8], [9], [10] represent, in many respects, a continuation in the direction first established by Curran and Craig in this early reference. Thrust-work-potential is 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. Other definitions have included ambient pressure as the reference point; it is recommended based on the results of [9] and this study that thrust-work-potential be evaluated based on an exit area rather than the ambient pressure, where possible. Engine thrust effectiveness is 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 denominator can be modified (if desired) such that the ideal flow is further expanded to ambient pressure, or, based on the earlier discussion, to infinite area.

Section II of this paper presents a simple combustor 'design' problem utilizing both the exergy and the 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. Section III 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 due to irreversibilities is also discussed. The conventional exergy-based method is shown in both Section II and III to yield less effective design information than the thrust-potential method. Section IV provides a discussion on the fluid and thermodynamic relationships between thrust-potential and conventional exergy in order to clarify the results obtained in Section II and III. Finally, Section V introduces the 'engine-based' exergy which 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.

II. Component Design Using Exergy and Thrust-Based Efficiencies

In order to examine and contrast the exergy-based rational efficiency method and the thrust-potential based engine effectiveness method for the design of high-speed aerospace engines and engine components, a very simple and easily duplicated design problem is posed. Any method which 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 is enforced or whether isentropic flow in a specific component is specified.

Consider a highly simplified scramjet as shown in Figure 1. The flight Mach number is 12, the ambient temperature is equal to 200K and the ambient pressure is equal to 1kPa. Let the gas flow throughout the scramjet engine be air with C_p = 1005 J/kgK and γ = 1.4. 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) is constant at ΔQ_{expend} = 1000000 J/kg (air); however, the heat released into the flow is scheduled such that a 'combustion' efficiency, η_c, is modeled where



Isentropic inlet (shockless/frictionless)
In combustor: $C_f = .02$
Q (release) controlled by combustion efficiency (input)
Isentropic nozzle (except for comparative studies)
One-dimensional flow

Note: problem statement forces external aerodynamics to remain the same regardless of L_c (optimal)

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

$$\eta_c = \frac{\Delta Q_{released}(x)}{\Delta Q_{expend}} \quad (1)$$

The combustion efficiency distribution utilizes an exponential distribution with x (see Figure 2) which approximates an actual η_c distribution in a true scramjet flow-field which 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 versus axial distance for all cases. The skin friction coefficient in the combustor is .02. For the initial investigation, the nozzle is assumed to be isentropic and the nozzle exit area is set equal to the inlet face area (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 optimal combustor length (L_{opt}); any combustor length greater than L_{opt} will result in a loss in performance. This is due to the fact that the cumulative heat released into the flow is asymptotic to the expended energy (ΔQ_{expend}); progressively smaller amounts of heat are released into the flow per unit length as the combustor lengthens. Due to the 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. This basic example provides a simple illustration of the problem of assessing mixing enhancement in scramjet combustors. The design "challenge" is to find L_{opt}, the combustor length which optimizes the performance of the vehicle. This will be done by utilizing both the rational efficiency method (which is exergy-based) as described in [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 one meter combustor length.

The rational efficiency (Ψ) is plotted in Figure 3 as a function of the axial distance along the combustor. The rational efficiency is defined in a matter consistent with [4], i.e., it is measured from the ambient conditions (T_o, S_o) at the inlet entrance (at zero velocity),

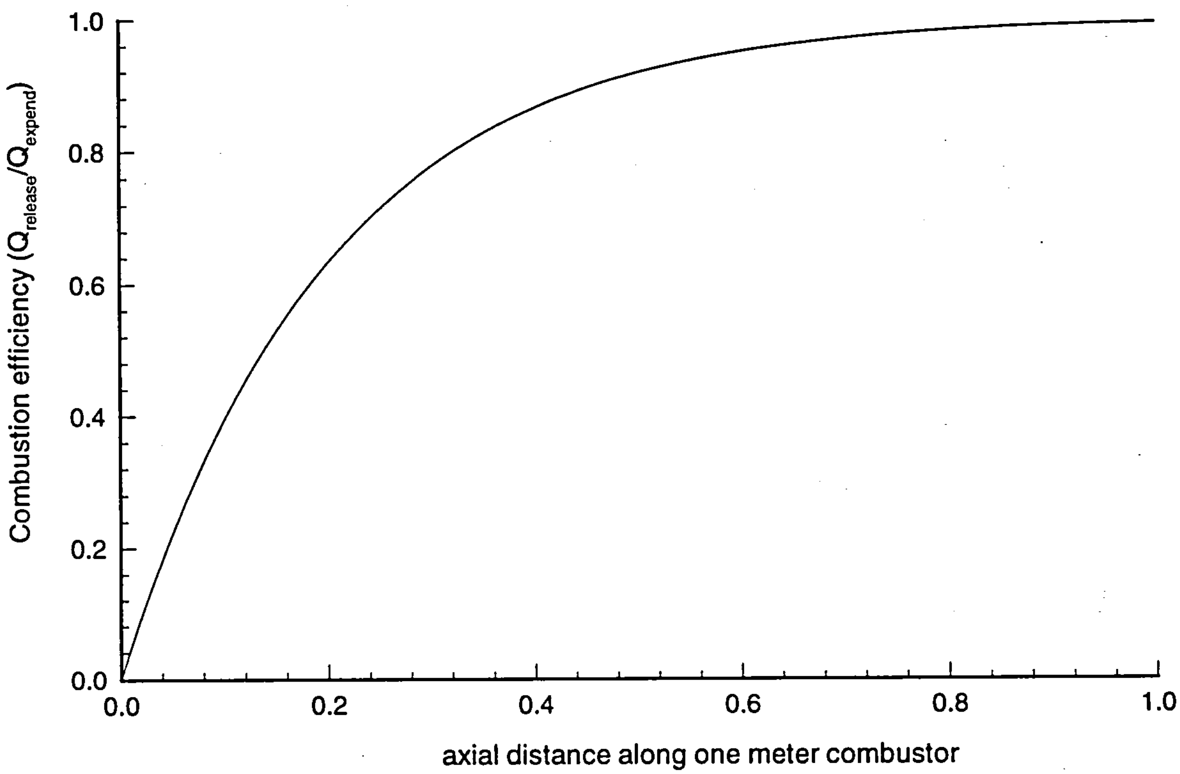


Fig. 2 "Combustion" efficiency model versus x showing release distribution of heat

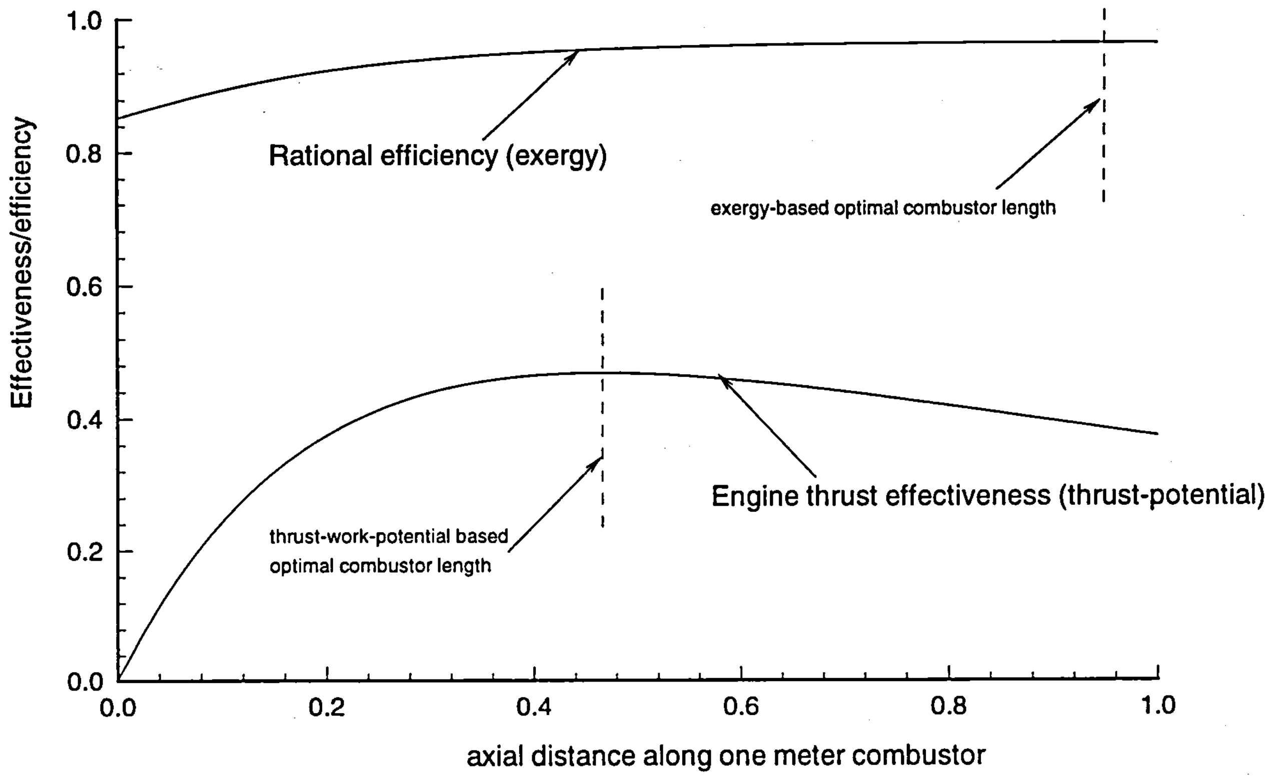


Fig. 3 Rational efficiency (exergy) and engine thrust effectiveness (thrust-potential) versus axial distance along combustor showing optimal lengths for both parameters

or at a station x:

$$\psi(x) = \frac{\int_{o}^{x} \delta Q_{released} + \frac{u_o^2}{2} - \int_{o}^{x} T_o ds}{\Delta Q_{expend} + \frac{u_o^2}{2}} \tag{2}$$

The rational efficiency predicts an optimal combustor length of .952 meters, i.e., ψ (or exergy) is a maximum at this axial location in Figure 3.

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:

$$\eta_{ee}(x) = \frac{\dot{m}u_e(x) + P_e(x)A_e - (\dot{m}u_o + P_oA_o)}{\dot{m}u_{e_{ideal}} + P_{e_{ideal}}A_e - (\dot{m}u_o + P_oA_o)} \tag{3}$$

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

The thrust-potential based engine effectiveness distribution is seen in Figure 3 to be maximized at .46, i.e., an optimal combustor length of .46 is predicted. This is approximately 50% of the optimal length predicted utilizing the exergy-based rational efficiency. This result illustrates the fundamental difference between component designs obtained utilizing the two methods even for this highly simplified case in which a single design parameter (L_{opt}) is sought.

The actual engine thrust effectiveness is plotted again in Figure 4 versus the axial distance along the combustor. Also shown, however, are calculated losses in this parameter due to irreversibilities associated with friction and heat addition at finite Mach number (Rayleigh losses) as well as the loss due to incomplete heat release. These losses are computed by utilizing a technique developed in [9] which can identify and quantify losses in engine thrust (or station thrust-potential) due to coupled irreversibilities and incomplete

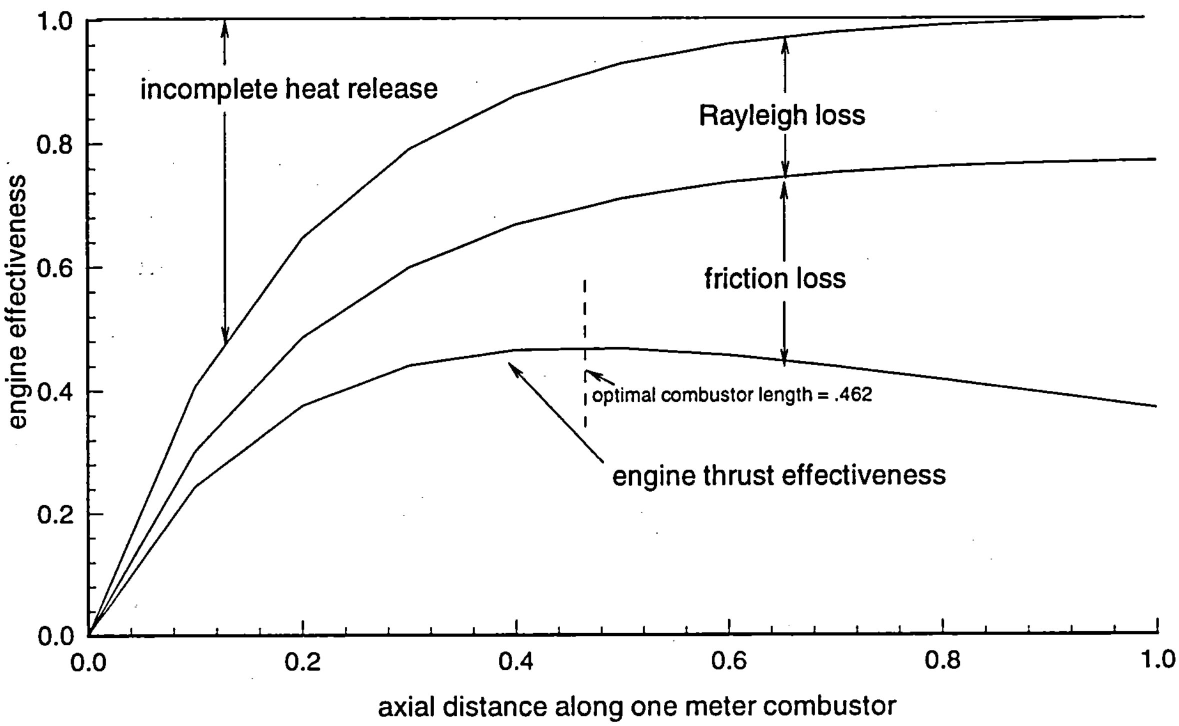


Fig. 4 Engine thrust effectiveness and losses versus axial distance along combustor

combustion. This technique will be discussed further in Section III. The engine thrust effectiveness is maximized at the axial station at which the sum of the lost thrust due to irreversibilities and due to heat addition is minimized. In fact, the engine thrust effectiveness, η_{ee}, can be defined as

$$\eta_{ee} = \frac{FW_{ideal} - \Delta FW_{irr} - \Delta FW_{incomp}}{FW_{ideal}} \quad (4)$$

where FW denotes thrust-work, ΔFW_{irr} is the lost thrust work due to irreversibilities, and ΔFW_{incomp} is the lost thrust work due to incomplete heat-release.

The distribution of losses for the exergy-based rational efficiency is given for this problem in Figure 5. Losses are due to friction, Rayleigh heat addition, and incomplete heat-release. There is an additional loss shown for this method which is neither a loss due to irreversible mechanisms 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 (Figure 4) and the exergy-based method (Figure 5).

Figure 6 plots actual net thrust of the engine for various actual combustor lengths. The maximum engine net thrust is obtained when a combustor length of .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 thrust occurs is shown by the pattern of triangular symbols in Figure 6. The actual optimal length of the combustor changes marginally from .46 to .5 meters 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

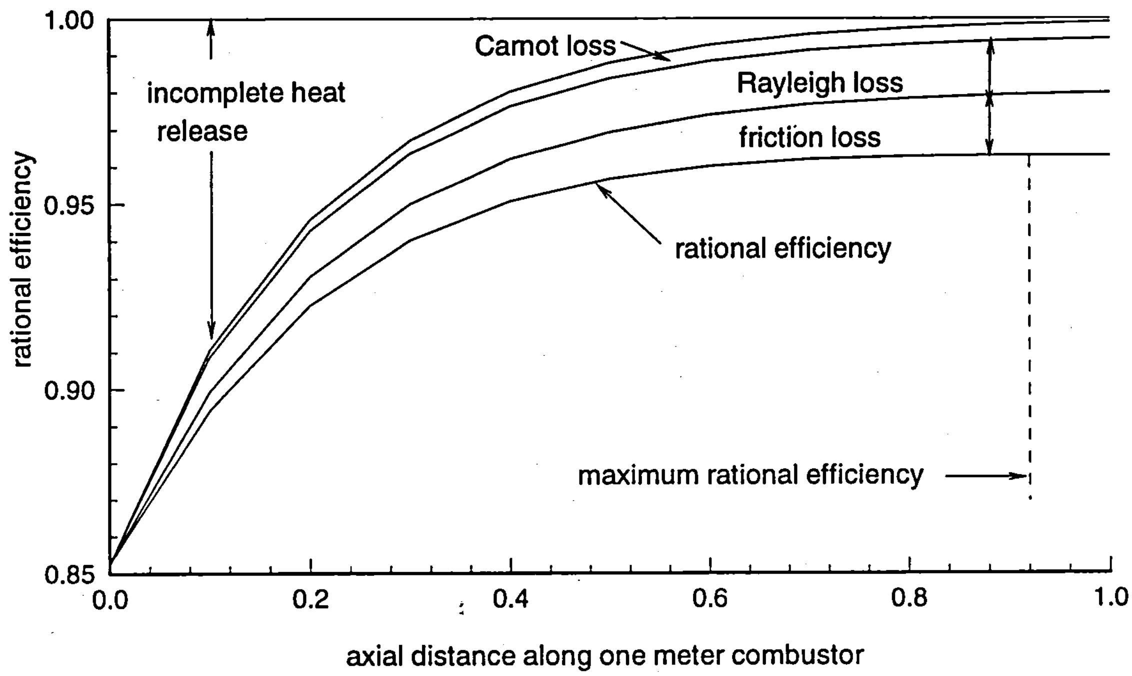


Fig. 5 Rational efficiency and losses versus axial distance along combustor

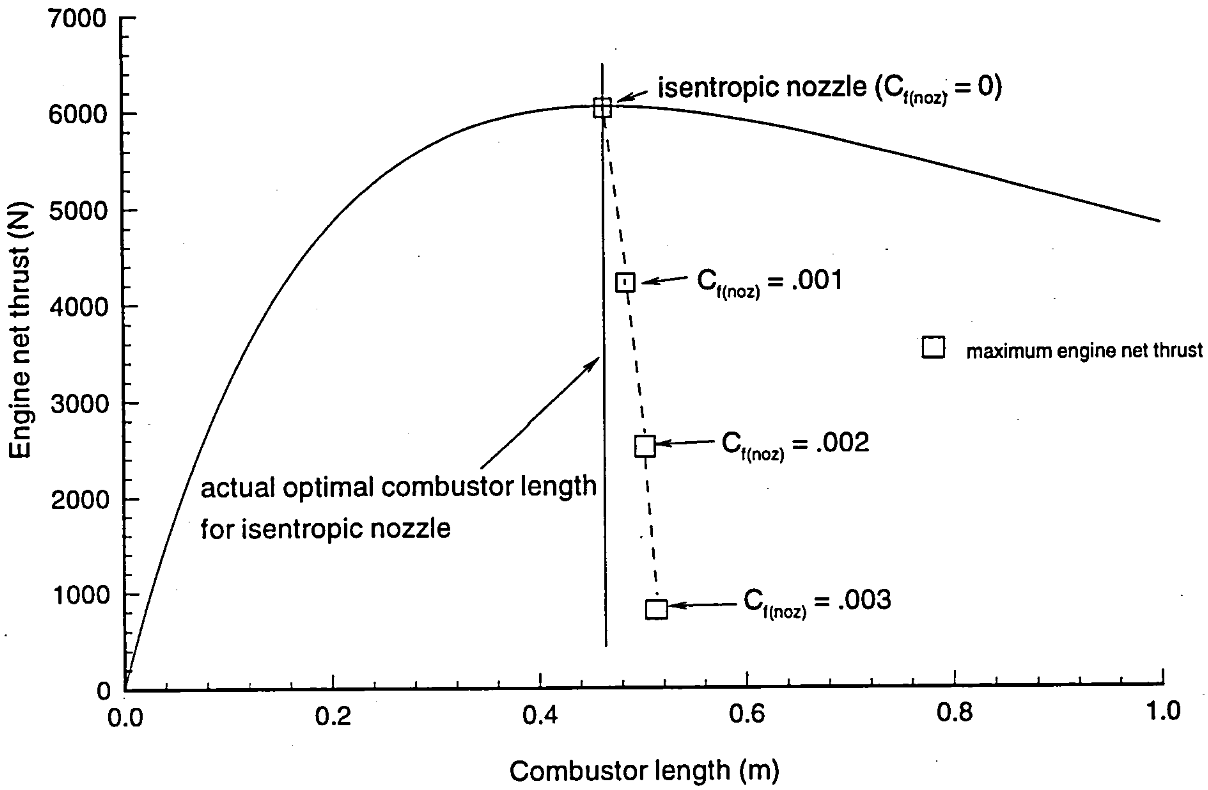
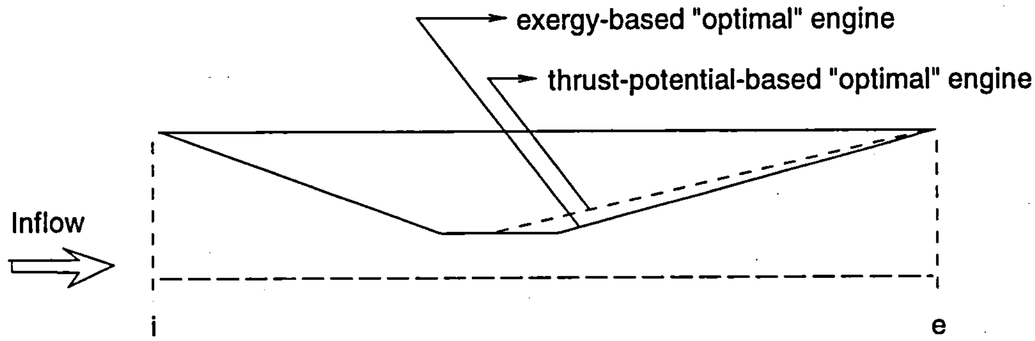


Fig. 6 Actual engine net thrust versus combustor length chosen for range of nozzle skin friction coefficients

of interest (although such losses may be approximated if desired by simple modifications to the methods).

A summary of the two 'optimal' designs obtained by using the two methods is presented in Figure 7. Note that the 'external' aerodynamics has not been allowed to change in this particular investigation; the only geometric effects are (as shown) i) the shorter combustor for the thrust-potential configuration and, ii) consequently, since the overall engine length is to be maintained, a slightly longer nozzle and less severe of an expansion angle for this configuration. However, the flow in the actual nozzle is driven only by the nozzle-to-combustor area ratio (under the restriction of isentropic one-dimensional flow); this ratio is identical for both optimal 'designs'. Figure 7 illustrates that the exergy-based method yields an engine design which 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 Figure 8 for a range of nozzle skin friction coefficients. Several observations can be made by examining Figure 8. 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) predicts an optimal combustor length which is entirely independent of the degree of expansion and which 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 both component and engine design. By extension, the performance assessment technique used for either component or engine design *must* account for this degree of expansion. Each engine component should be optimized with respect to the engine; in addition, within the iterative vehicle design process itself, the engine should be optimized with respect to the vehicle and the vehicle optimized with respect to the overall mission.



Optimal engine summary

Thrust-potential method	Exergy method
combustor length = .462m	combustor length = .926m
engine net thrust = 6044N	engine net thrust = 4810N
Q (expended) = 1E06 J/kg	Q (expended) = 1E06 J/kg
Same external aerodynamics	Same external aerodynamics

Fig. 7 Summary of "optimal" engines based on exergy and thrust methods

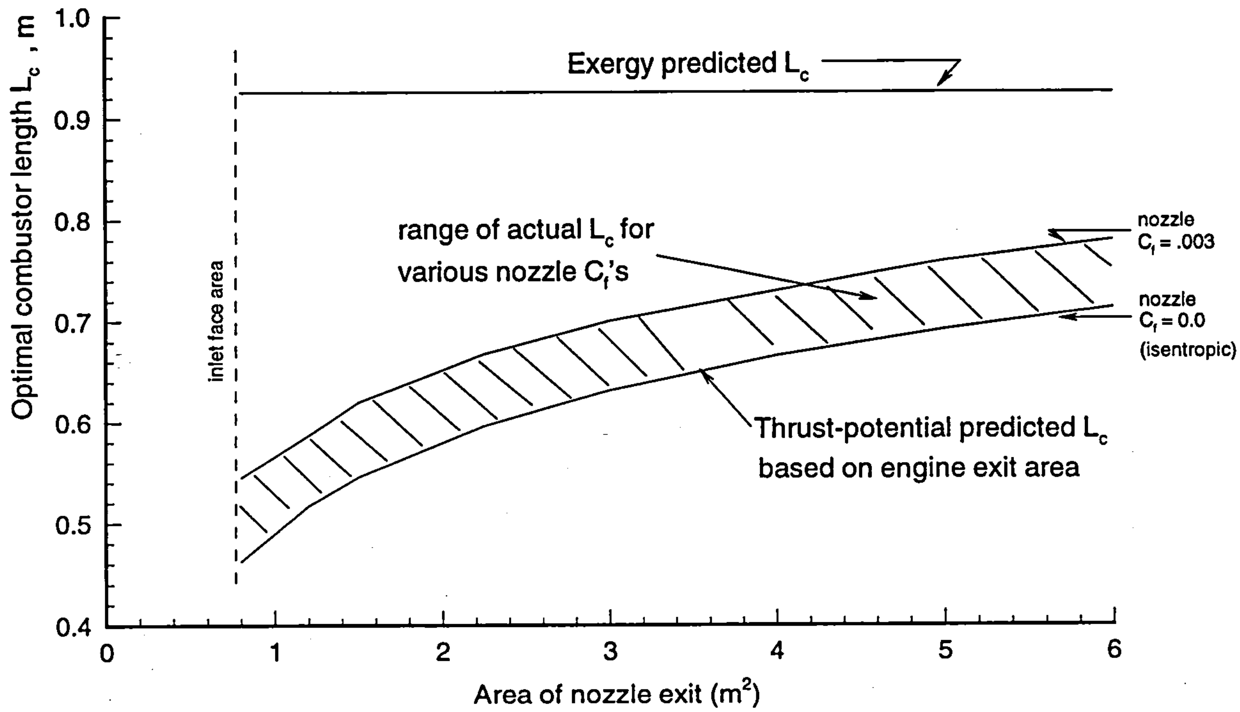


Fig. 8 Influence of degree of expansion on optimal combustor length including exergy-based and thrust-potential optimal lengths

III. Identification of Component Losses Using Exergy and Thrust-Based Methods

It is important that the successful performance assessment method consistently yield accurate information as regards flow losses, i.e. the method should be able to discriminate and quantify performance losses due to 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 generally assess component performance losses in terms of the exergy losses which 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 due to a particular loss mechanism is associated. This method works either in terms of thrust-potential or in terms of loss in raw streamthrust at a given station. In addition, the fundamental 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 constant-area duct with friction (C_f = .002) as shown in Figure 9. Let the inflow conditions be U = 2000 m/s, T = 620K, and P = 1000 N/m^2. The length of the duct is 10 meters. There is no heat addition in this duct; the total enthalpy then remains constant. Assume air with constant properties (C_p = 1005 J/kgK and γ = 1.4). This flow has only one possible propulsively useful performance descriptor - drag (or streamthrust loss). There will, however, be both measurable exergy losses as well as streamthrust losses (drag) as measured from the duct inflow values. Let the duct be arbitrarily sectioned at the 3.333 meter location (one-third of the way along the duct axis - at point 'b') and call the upstream 'component' Y and the downstream 'component' Z. Y has some quantifiable irreversible entropy increase (per unit mass), ΔS_y = 281 J/kgK. Likewise Z has some different quantifiable irreversible entropy increase, ΔS_z = 271 J/kgK. Using the one-dimensional flow equations, the streamthrust at 'b' is calculated as 885 N while the streamthrust at the end of the duct ('e') is calculated as 797N. This indicates a streamthrust loss (or drag) of 50.6N for component Y and 88N for

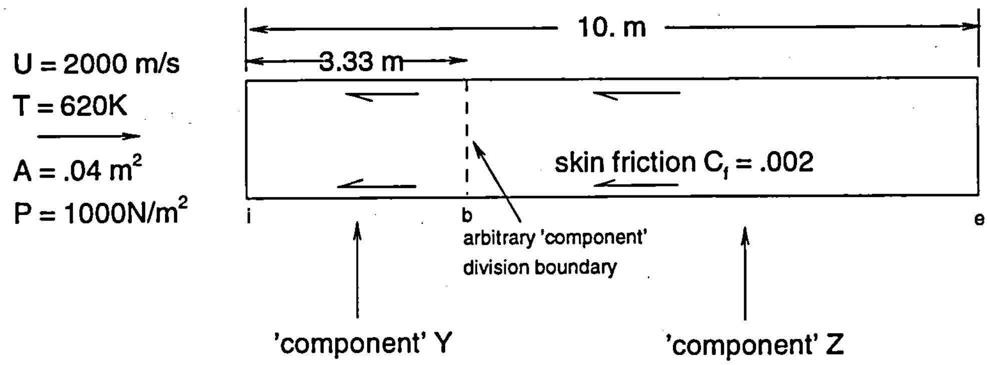


Fig. 9 One-dimensional duct with friction showing arbitrary 'component' division boundary

component Z. Note that component Z has a far greater streamthrust 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

$$\Delta Ex_{loss} = T_o(\Delta S_y + \Delta S_z)$$

Hence ΔEx_y = 174220 J/kg and ΔEx_z = 168020 J/kg. These 'component' exergy losses are then simply proportional to the particular 'component' entropy gain and do not yield the performance information noted above that the Z component (the downstream component) has a much greater performance loss than component Y (the upstream component), relative to its entropy gain.

In order to calculate the lost streamthrust utilizing the method developed in detail in [9], the exit flow of the duct is expanded isentropically utilizing the relation

$$\frac{A_e(\text{expanded})}{A_e} = e^{\frac{\Delta S}{R}} \tag{5}$$

where R is the gas constant. The expansion is performed by sequentially utilizing the entropy increases from downstream component to upstream component (this process and its thermodynamic basis are explained in [9]). This process yields the exit streamthrusts for increasingly reversible flow-fields (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 the specific thrust losses due to specific irreversible mechanisms can be made. In addition, the component (or engine location) with which each particular thrust loss is associated can be rigorously identified. It is important to understand that this method of expanding the actual flow in order to recover (and hence 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 due to upstream irreversibilities as described in [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 streamthrust 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 above, this method, when suitably applied using the component entropy increases, should simply return the streamthrust at 'b' when the lost streamthrust (drag) of component Z is calculated by an initial expansion of the exit flow and then return the streamthrust at the duct inflow when the lost streamthrust of component Y is further calculated from another subsequent expansion. Figure 10 depicts this expansion process (note that no thrust-potential issues are involved here). Lost thrust in component Y utilizing this method is computed as 50.6N; lost streamthrust in component Z utilizing this method is 88N. 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 streamthrust loss due to 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 identify the correct component and yields no useful propulsive information. Exergy losses simply scale directly with entropy losses while streamthrust losses, thrust-potential losses, and engine thrust losses associated with irreversibilities within a component are not linearly scaled by the entropy increases associated with a component. In addition, when the streamthrust obtained by expansion of the duct inflow within a nozzle (or, identically, the streamthrust obtained by expansion of the flow at the duct exit for an isentropic duct) is compared to the streamthrust obtained by expanding the actual flow at the duct exit within a nozzle, losses in obtainable streamthrust are seen to vary significantly with the degree of nozzle expansion. Figure 11 shows the streamthrusts for such an expansion process versus nozzle exit area; the top curve is the (expanded) streamthrust for

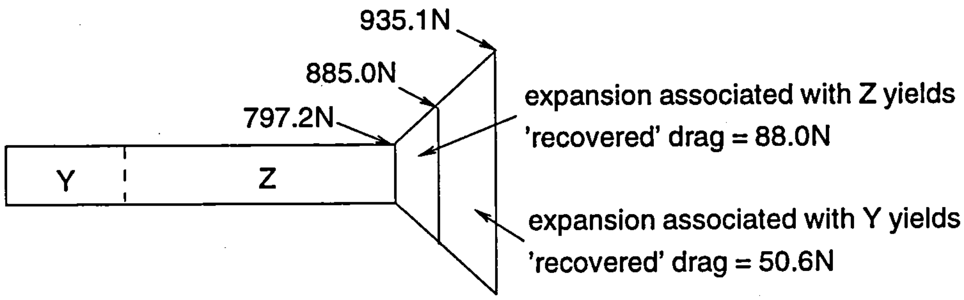


Fig. 10 Schematic of lost streamthrust recovery method for use in thrust or thrust-potential engine analysis

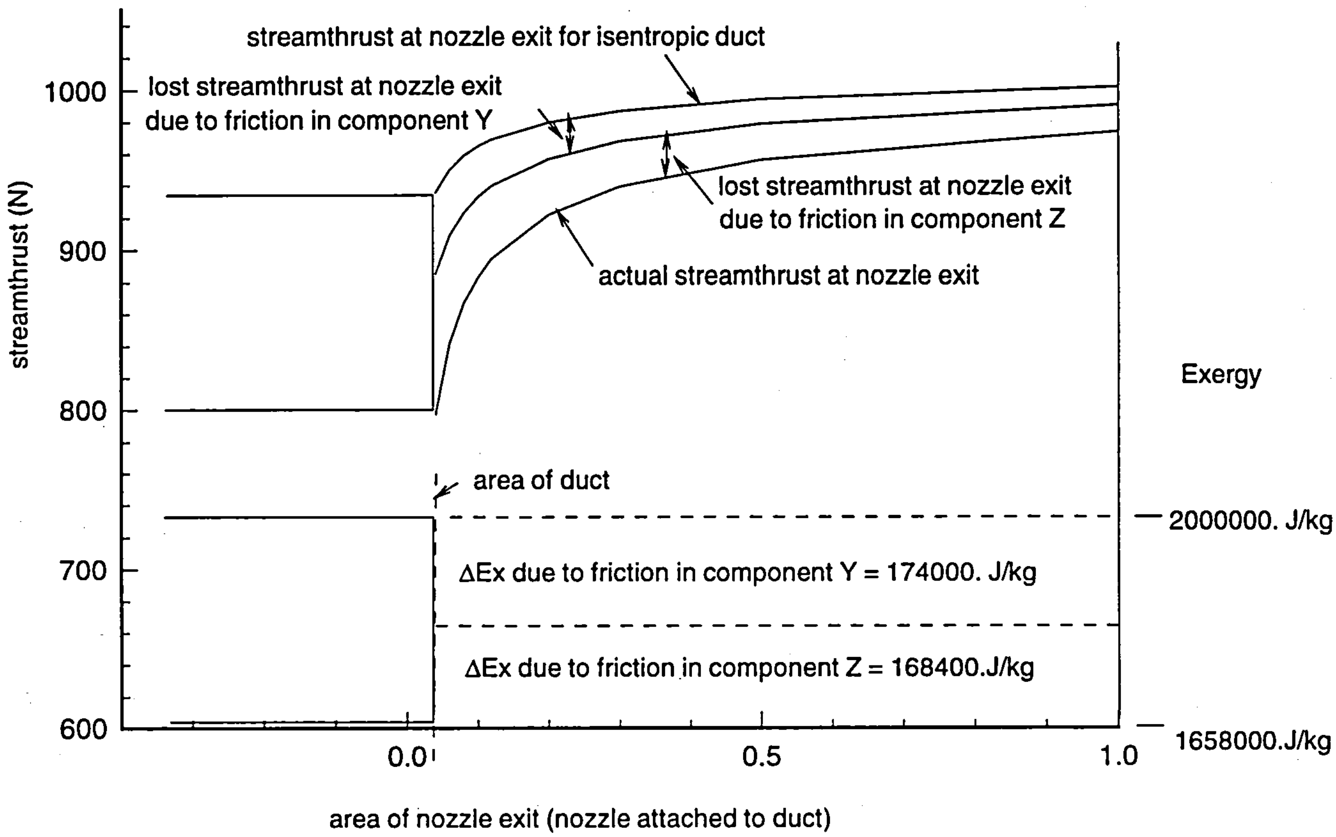


Fig. 11 Influence of degree of expansion on nozzle streamthrust obtained for one-dimensional duct with friction; lost thrust associated with components also shown (bottom - exergy losses associated with components)

an isentropic duct, the bottom curve is the (expanded) streamthrust for the actual duct with losses. The region between these two curves is divided into thrust losses associated with component Y and component Z. These losses are computed (after the flow is first expanded to the nozzle exit area) by using the technique discussed above for quantifying lost component thrust. The influence of the losses is seen to diminish as the degree of expansion is increased. At infinite expansion, there is no measurable lost thrust due to irreversibilities. As shown on this same figure, 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.

In order to further illustrate the issues involved with assessing component performance losses (and directing component optimization efforts) by using both the exergy method and the thrust-potential method (in conjunction with the lost thrust technique described above), the simple scramjet problem analyzed in the previous section (II) will be revisited. This problem originally posed the optimal length of the combustor as the desired 'design feature'; in this section, the combustor length will be fixed at one meter and the combustor will be arbitrarily divided into two 'separate' components, Y and Z, in a manner similar to the previous one-dimensional duct with friction. This situation is depicted in Figure 12. Both the exergy method and the thrust-potential method will then be used in order to determine the losses due to irreversibilities within these two components. There are two (coupled) loss mechanisms in this flow; they are associated with heat addition at finite Mach number and skin friction. The former losses will be termed the 'Rayleigh' losses as opposed to the friction losses.

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 one meter combustor length and constant skin friction of $C_f = 0.02$ in the combustor) is given below:

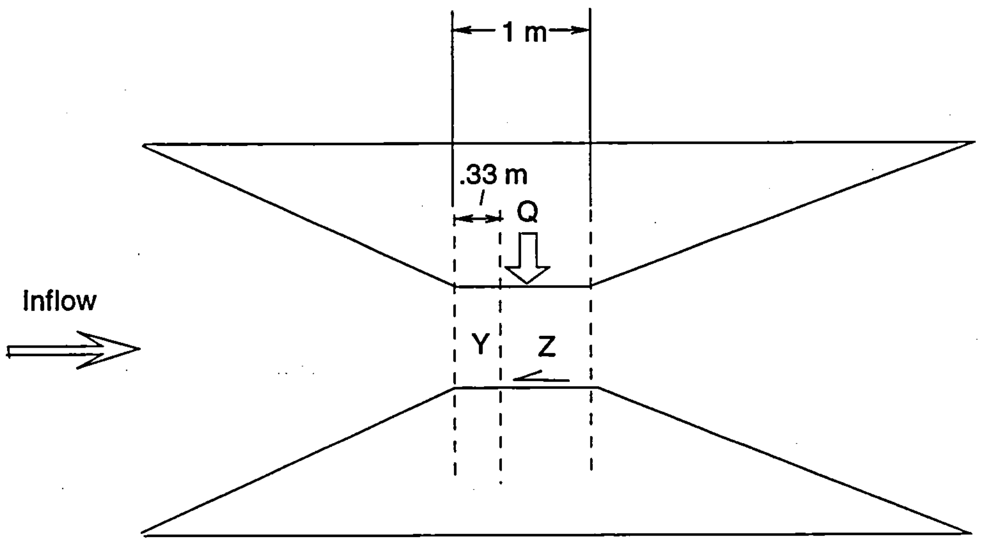


Fig. 12 Schematic of simple scramjet engine showing arbitrary sectioning into "components" for loss analysis

engine net thrust: 4727N

lost engine thrust due to:
friction in Y:2259N
friction in Z:2582N
Rayleigh burning in Y:2858N
Rayleigh burning in Z:362N

entropy gain due to:
friction in Y:349J/kgK
friction in Z:226J/kgK
Rayleigh burning in Y:467J/kgK
Rayleigh burning in Z:31J/kgK

lost exergy due to:
friction in Y:69800J/kg
friction in Z:45200J/kg
Rayleigh burning in Y:93400J/kg
Rayleigh burning in Z:6200J/kg

ΔS_{rev} = 155 J/kgK

The exergy loss due to friction is greatest in component Y; therefore, based on this method, component Y should be selected for loss reduction. The thrust loss due to friction is greatest in component Z; based on the thrust-potential method, component Z should be selected for loss reduction. When the design procedure as outlined before is followed, the engine is improved by eliminating skin friction within the identified component. Figure 13 provides a brief 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 due to the individual loss mechanisms is shown in Figure 14. The effect of the irreversibilities on the delivered net thrust of the engine diminishes as the degree of nozzle expansion is increased. Conversely, the exergy losses are independent of the degree of nozzle expansion, as discussed earlier. Figure 15 plots the overall engine efficiency (i.e., the ratio of the actual net thrust to the energy expended) and the various losses in the overall engine efficiency due to the various irreversibilities for a range of nozzle exit areas. The top curve corresponds to the ideal engine with the given nozzle exit area while the bottom curve corresponds to the overall efficiency of the actual engine at the same exit area. The losses due to the individual mechanisms are quantified using the technique discussed above in which lost thrust is directly related to increases in irreversible entropy.

exergy loss due to friction greatest in component Y:
select Y for 'loss reduction'

thrust-potential loss due to friction greatest in component Z:
select Z for 'loss reduction'

Summary of engine performance after 'identification' of component with major frictional losses and 'optimization' (reduction of frictional losses in that component)

'optimal' engine summary (for identification of component performance losses)

Thrust-Potential Loss Method	Lost Exergy Method
engine net thrust = 7555N	engine net thrust = 6001N
heat energy cost = 1000000 J/kg	heat energy cost = 1000000 J/kg
same engine geometry	same engine geometry
same external aerodynamics	same external aerodynamics

Fig. 13 Summary of "optimal" engines after component loss identification/optimization

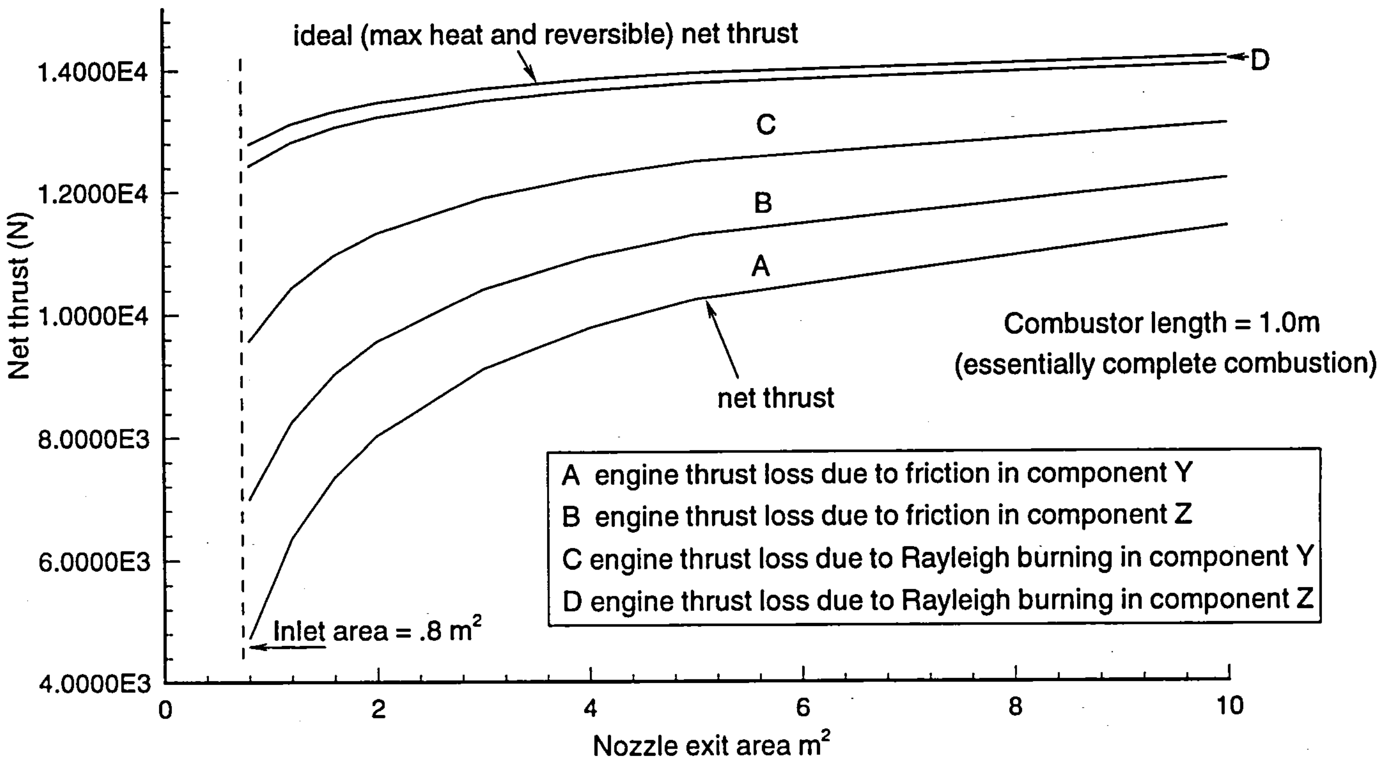


Fig. 14 Net thrust and component and mechanism losses versus nozzle degree of expansion

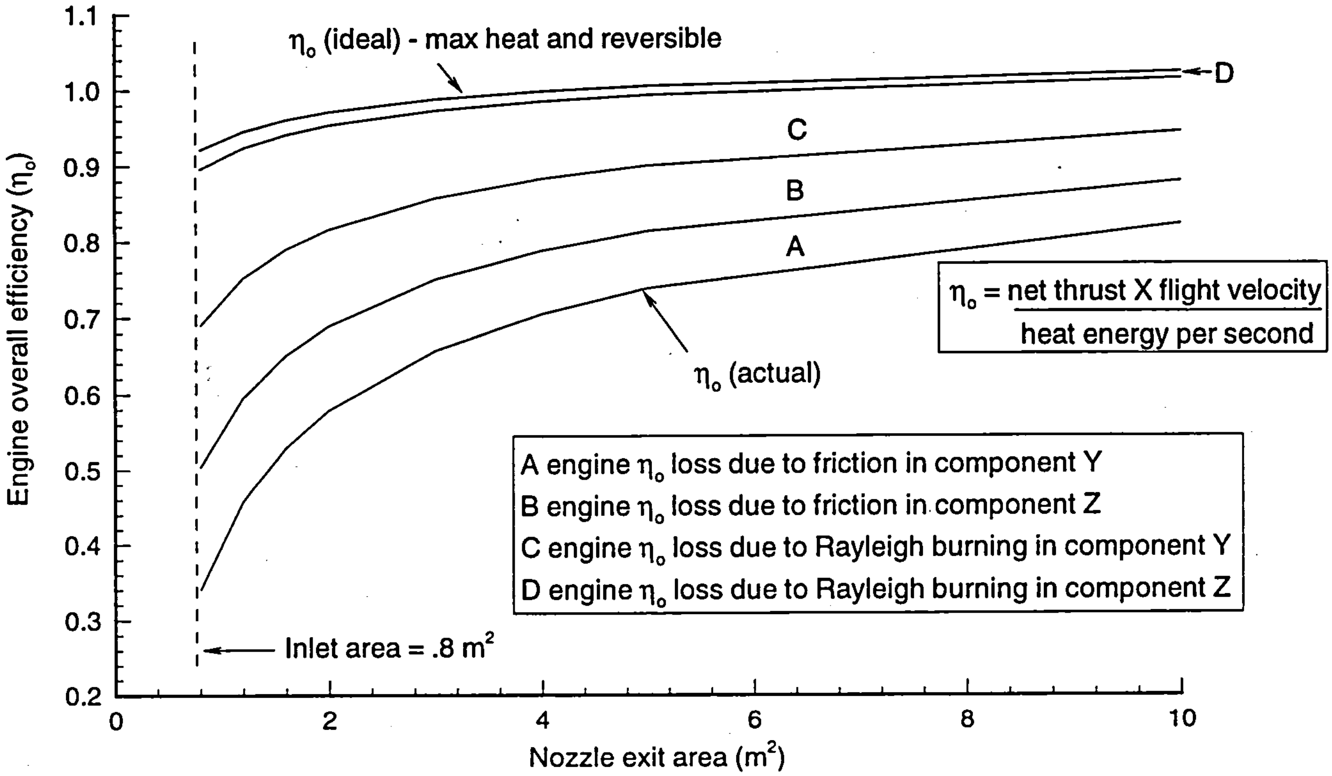


Fig. 15 Overall engine efficiency and component and mechanism losses versus nozzle degree of expansion

IV. Fluid-thermodynamic Relationships Between Exergy and Thrust

The previous two sections in this paper (II and III) describes simple problems in which the exergy method fails to deliver adequate information for either engine component design and assessment or for loss identification and assessment. This section reviews the thermodynamic and fluid dynamic basis of both standard exergy and thrust as applied to an aerospace engine. This is done in order to explain the results obtained in earlier sections and to understand the relationships between these two methods.

Exergy or energy availability is conventionally defined as the maximum reversible work which can be attained from a gas at a given thermodynamic and fluid dynamic state as measured from an equilibrium reference state (often referred to as the dead state.) The reference state is usually chosen to be that corresponding to ambient temperature and pressure (hence ambient entropy) and zero velocity. For a gas of fixed composition throughout the engine with Rayleigh heat addition, this is an adequate description of the reference state and allows a complete (or closed) cycle with exact return of the working gas to the ambient conditions. For a gas with variable composition (as in a real engine), the concept of 'returning' the flow to exactly the conditions at the engine inlet is impossible due to the presence of fuel by-products in the exhaust gas. The most that can be done is to enforce chemical equilibrium of the exhaust at the ambient temperature. In this sense, then, the closure of the cycle for a real engine is impossible. However, this investigation does not address these additional issues concerning exergy methods but instead seeks to demonstrate and address even more fundamental concerns when exergy methods are applied without appropriate modification to highly simplified engine configurations utilizing Rayleigh heat addition.

The change in availability (or exergy) from the flow at some location x (see Figure 16 for station numbering) for a 'simple' engine (one with fixed gas composition, Rayleigh heat addition, and constant specific heats) is given as follows:

$$Ex(x) = C_pT(x) + \frac{u(x)^2}{2} - (C_pT_o + \frac{u_o^2}{2}) - T_o(s(x) - s_o) \qquad (6)$$

The exergy at the engine exit can be equivalently described as equal to the closed cycle line

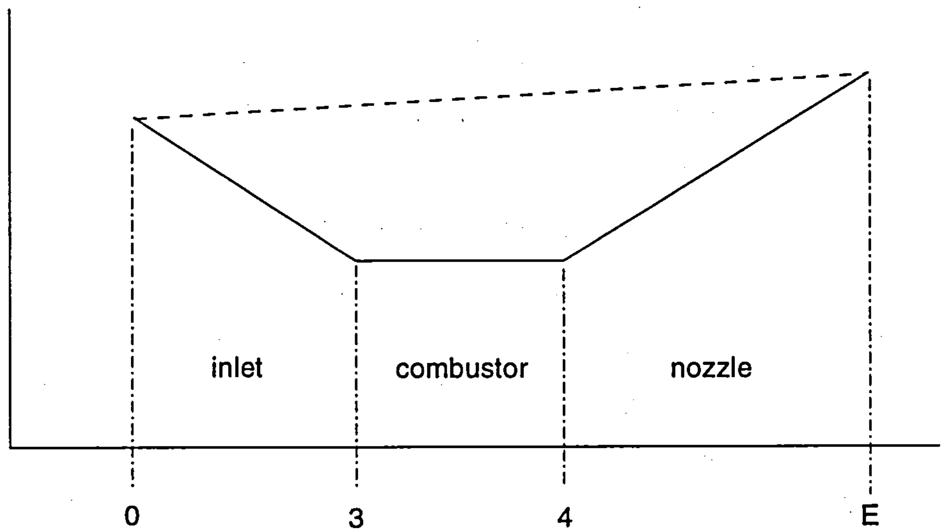


Fig. 16 Schematic showing scramjet station numbering for use in T-S diagrams and discussions

integral of the gas expansion work per unit mass (minus the frictional work per unit mass) with the integration path and direction as indicated on a temperature-entropy (T-S) diagram (Figure 17). This integration path follows the clockwise path 0-3-4-E-E_o-0. The E-E_o path corresponds to an isentropic expansion to ambient temperature (T_o) and the E_o-0 path is the wake heat-rejection leg of the cycle. This integral definition of exergy is written as follows:

$$Ex(E) = \int_o^o Pdv - \int_o^E Tds_{viscous} \tag{7}$$

When the value of exergy is defined at some intermediate location in the engine (for example in the combustor between stations 3 and 4) the path diagram follows the path shown in Figure 18. The isentropic gas expansion leg from x to $E_o(x)$ passes through an intermediate temperature, T (E(x)), at which the area of the gas streamtube is exactly equal to the actual exit area of the engine. It can be seen from these figures that exergy is an inherently closed (or complete) cycle-based parameter and that the value of exergy does not change between x and E_o (x). Therefore, exergy (or any exergy-based parameter) is unrelated to the degree of nozzle expansion either for the actual engine or when assessed at a particular point within the engine flow-path.

Engine net thrust for the simplified engine (Rayleigh heat addition, constant specific heats, and one-dimensional flow) can be defined as the summation of all pressure and viscous axial forces throughout the engine, i.e.,

$$F(Net) = \int_o^E dF \tag{8}$$

where $dF = PdA - dR_{viscous}$.

By Newton's second law, this is equal to the change in the streamthrust ($\dot{m}u + PA$) from engine face to engine exit. However, for the purposes of directly relating performance to the T-S diagram, the integral form (8) is more useful. The engine thrust work per unit mass can be defined as

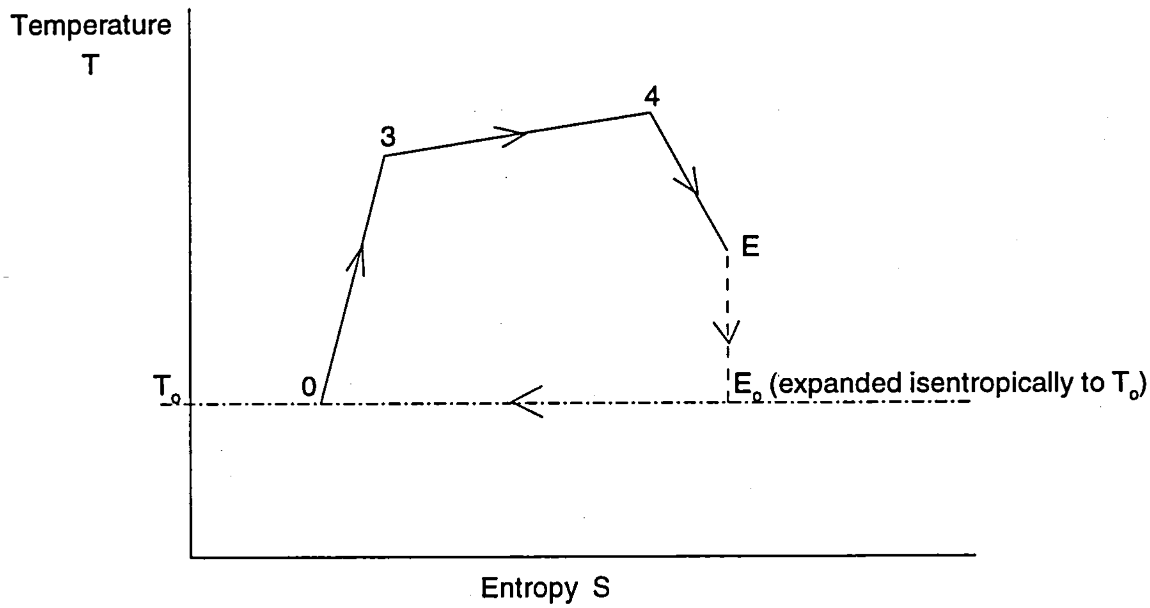


Fig. 17 Temperature-entropy diagram showing integration path for exergy calculation and thrust calculation

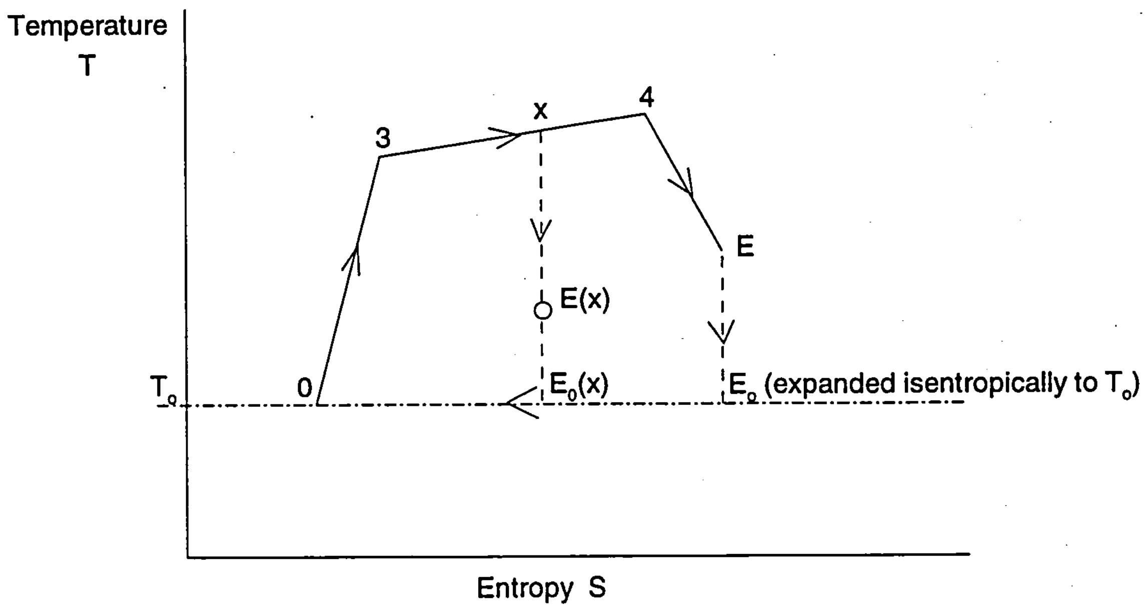


Fig. 18 Temperature-entropy diagram showing integration path for intermediate exergy calculation and thrust-potential calculation

$$FW = \int_{o}^{E} \frac{U_o dF}{\dot{m}} \tag{9}$$

where U_o is the flight velocity and $\dot{m}$ is the engine mass flow rate. When the value of thrust potential is established at some intermediate location in the engine (i.e., in the combustor between 3 and 4), an isentropic gas expansion process is followed just as in the exergy evaluation. However, this process is terminated at E(x) in Figure 18. The following expression for thrust-work-potential can then be written:

$$FWP = \int_{o}^{E(x)} \frac{U_o dF}{\dot{m}} \tag{10}$$

It is obvious that relationships between engine (exit) exergy and engine net thrust-work and intermediate exergy and intermediate engine thrust-work potential will be similar since both methods rely on an isentropic expansion (entirely analogous to an isentropic nozzle) from the intermediate station-of-interest through the actual engine nozzle exit area. This expansion continues to T_o for the evaluation of the exergy.

From equation (7), the exergy of the engine is:

$$Ex = \int_{o}^{o} Pdv - \int_{o}^{E} Tds_{vis}$$

or, breaking this integral apart,

$$Ex = \int_{o}^{E} Pdv + \left. \int_{E}^{E_o} Pdv - \int_{o}^{E_o} Pdv \right)_{T=T_o} - \int_{o}^{E} Tds_{vis} \tag{11}$$

The first integral is the cumulative gas expansion work from inlet to exit while the last integral is the cumulative frictional work from inlet to exit. These two integrals are the contributions to the exergy which are associated with the engine flow-path itself. The second and third integral are both external to the engine (wake process); the second integral is the isentropic gas expansion to the ambient temperature, T_o, while the third integral is the wake heat rejection process which occurs at T_o.

For a fluid element of unit mass moving with velocity u through a diverging duct (as in a nozzle), the differential gas expansion work can be readily broken into two contributions, one associated with that part of the volumetric expansion in the cross-sectional direction (a dA term) and the other with that part of the volumetric expansion in the axial direction (a dx term), or

$$Pdv = \frac{uPdA}{\dot{m}} + RT\frac{du}{u} \tag{12}$$

In an isentropic nozzle, the PdA term is the 'productive' part of the gas expansion work since it is associated with the differential reaction thrust force (dF) which the vehicle structure experiences as a result of the gas expansion. Hence, in general, all gas expansion work is not convertible to 'gas thrust' work. From equation (12) and the definition of dF, the following expression is written:

$$\int_o^E Pdv - \int_o^E Tds_{vis} = \int_o^E \frac{udF}{\dot{m}} + RT\frac{du}{u} \tag{13}$$

This follows since

$$\int_o^E Tds_{vis} = \int_o^E \frac{udR_{vis}}{\dot{m}} \tag{14}$$

It should be emphasized that the term udF is associated with the cross-sectional expansion work performed by the gas element within the engine whereas the term U_odF is the differential thrust work experienced by the engine. The connecting 'bridge' between the two expressions is the differential force, dF. This dF is experienced by the working gas moving at local gas velocity u while it is experienced by the vehicle structure moving at velocity U_o. The above integral equations can be rearranged to yield a final expression for the exergy in terms of dF:

$$Ex(E) = \left.\left.\int_{o}^{E}\left[\frac{u}{U_o}\left(\frac{U_o dF}{\dot{m}}\right) + RT\frac{du}{U}\right] + \int_{E}^{E_o} Pdv\right)_{\substack{\text{to } T_o \\ \text{(Reversible)}}} - \int_{o}^{E_o} Pdv\right)_{T = T_o} \tag{15}$$

This expression relates conventional exergy to the differential thrust work and clearly shows the terms involved in the exergy which are external to the engine. 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 $Pd\nu$ work) if the wake of the engine was suitably processed (with an isentropic expansion to T_o and a heat-exchange device, etc.) and returned to the inlet face. An aerospace engine, however, is 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. By examining these observations and the supporting figures, the reason becomes evident for the initial prediction of a large optimal combustor length in the original example in this investigation when using the exergy method. 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 which is based on the true nozzle exit area. Since the losses have less impact at low temperatures, the combustor is 'allowed' to be longer in order to take advantage of additional heat release.

V. Engine-Based Exergy Analysis

The concept of available work (or exergy) can be readily used for the analysis of aerospace engines providing it is suitably redefined in order to account for the open-cycle nature of such engines. This section describes the development of an 'engine-based' exergy approach which enables the unification of thrust-based and exergy-based performance assessments. The following discussion is very similar to the analysis presented in [9] in which the thermodynamic background of the methodology of identifying and quantifying thrust losses due to irreversibilities is originally developed (see also section III). Any consistent evaluation of engine performance requires the definition of the completely reversible engine in order to establish the performance base-line for losses in engine performance due to irreversibilities. In addition, the ideal engine, which is both reversible and has complete heat addition, must be defined in order to measure the performance loss due to 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_o, T_o, M_o, the heat input ΔQ, the irreversibilities ΔS_{irr}, and the degree of expansion of the nozzle (A_e/A_o). The exergy (as previously and conventionally defined) is a function of the same variables with the exception that it is entirely independent of the degree of expansion (no A_e/A_o 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). In order to understand how the conventional definition of exergy should be modified in order to account for the open-cycle nature of aerospace engines, it is instructive to examine a T-S diagram for a scramjet engine (Figure 19). Both actual (irreversible) and reversible T-S paths for the engine with a given heat input, ΔQ, and a 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 $P_E \neq P_{ER} \neq P_o$ for a given nozzle exit area nor does the actual heat addition generally occur at constant pressure (or constant area) for realistic scramjet engines. Although such assumptions are often made in engine analysis, the concepts and techniques described in this and related investigations are completely general.

In Figure 19, a family of engines with differential irreversibilities removed progressively 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. The lost work between the completely reversible and the irreversible (actual) engine can then be integrated over this locus line as

$$LW_{irr} = \int_{ER}^{E} T dS_{irr} \tag{16}$$

This is shown as the hatched area in Figure 19. This lost work is equivalently the external

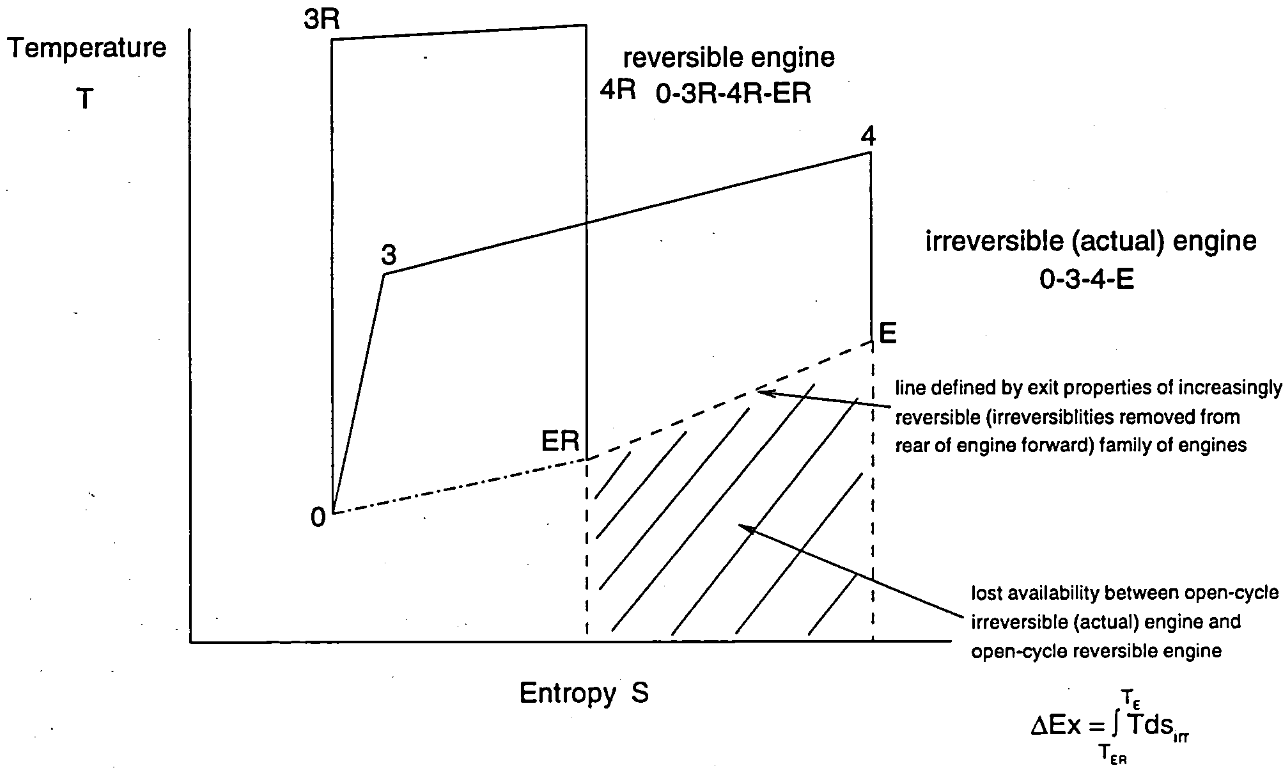


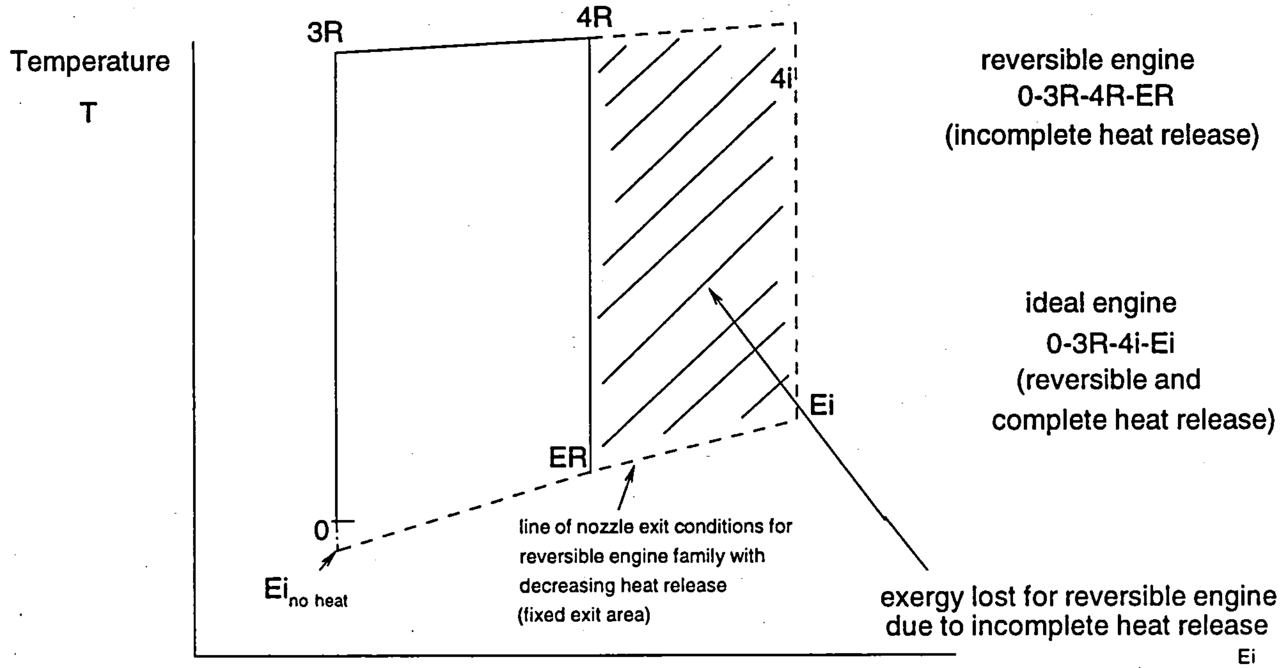
Fig. 19 Temperature-entropy diagrams for actual and reversible engines showing lost availability between the two engines

work required to process (using suitable differential thermodynamic processes) the actual nozzle exit flow such that it becomes identical with the reversible engine nozzle exit flow (at the same exit area). The differential lost work increment, $(T_{Exhaust}-T_o)ds$ above the usual differential unavailability term, $T_o\,ds$, represents additional (and inevitable) unavailability and occurs due to the fact that the actual engine (as well as the reversible engine and any intermediate engine) generally exhausts at a temperature well above the ambient temperature T_o. This unavailability must be accounted for if exergy methods are to be used for meaningful engine analysis. This equation for the lost work is closely related to the expression given in [9] for the thrust work lost due to irreversibilities:

$$LTW_{irr} = \int_{ER}^{E} \frac{U_o\, T ds_{irr}}{u} \tag{17}$$

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 downstream location to upstream location through the engine. Although the lost engine thrust is most easily quantified by appropriate isentropic expansion of the actual nozzle exit flow (see eq. 5), the degree of expansion necessary is formulated directly by enforcing equality of streamthrust between the 'expanded' flow and the corresponding reversible engine. The straight-forward application of this method of 'recovering' lost work utilizing either exergy (eq. 16) or thrust work (eq. 17) results in the ability to accurately analyze flows with coupled losses and to separate losses into contributions associated with various engine components and specific loss mechanisms.

The lost engine-based exergy associated with incomplete combustion can be illustrated by examining the T-S diagram (see Figure 20) 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 on this figure. Due to 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 due to incomplete heat release is indicated by the hatched area in this figure and is defined as



$$\Delta Ex_{incomp} = (\Delta Q_{expend} - \Delta Q_{Act}) - \int_{ER}^{Ei} T ds$$

Engine-based exergy of ideal engine

$$Ex_{ideal} = \Delta Q_{expend} - \int_{Ei_{no\ heat}}^{Ei} T ds$$

Fig. 20 Temperature-entropy diagrams for reversible engine with complete heat addition and with incomplete heat addition showing lost availability between two engines

$$\Delta Ex_{incomp} = (\Delta Q_{expend} - \Delta Q_{Act}) - \int_{ER}^{Ei} Tds \tag{18}$$

where ΔQ_{expend} is the maximum heat (added) or energy expended and ΔQ_{Act} is the actual heat added. Furthermore, the engine-based exergy of the ideal engine is given as

$$Ex_{ideal} = \Delta Q_{expend} - \int_{Ei\,(no\,heat)}^{Ei} Tds \tag{19}$$

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

$$Ex_{Act} = C_p(T_E - T_o) + \frac{u_E^2}{2} - \frac{u_o^2}{2} - \int_{Ei\,(no\,heat)}^{E} Tds \tag{20}$$

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 Figures 19 and 20. The portion Ei (no heat) - ER is the locus line of the exit conditions for a family of reversible engines with progressively increasing heat release while 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 which, though simpler, is shown not to be useful in engine analysis. The true engine-based available work (eq. 20) can be compared to the conventional available work given here as

$$Ex_{conventional} = C_p(T_E - T_o) + \frac{u_E^2}{2} - \frac{u_o^2}{2} - T_o(S_E - S_o) \tag{21}$$

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 station in the engine). This figure-of-merit is called here the engine-based rational efficiency; for evaluation of this quantity at an intermediate engine station, an isentropic expansion to the locus line ER-E is implied with subsequent 'recovery' of lost work due to irreversibilities located upstream of the station followed by recovery of engine-based exergy due to incomplete combustion at that station. An engine-based rational efficiency can be defined in the following manner:

$$\psi_E = \frac{Ex_{Actual}}{Ex_{ideal}} = \frac{Ex_{ideal} - \Delta Ex_{irr} - \Delta Ex_{incomp}}{Ex_{ideal}} \tag{22}$$

This parameter is similar in form to the engine thrust effectiveness (eq. [4]); in fact, the two figures-of-merit yield almost identical results when analyzing the simple engine flows described in this investigation. This can be readily seen in Figure 21, in which the engine-based rational efficiency is plotted versus combustor length for the original example used in this investigation. The optimal combustor length is predicted as .46 and the lost engine-based exergy distributions due to friction, Rayleigh losses, and incomplete heat release are very similar to those shown for the thrust based engine effectiveness (see Fig. 4). Small differences in results using the two methods are due to the fundamental inequality between gas expansion work and engine thrust work (see, for example, eq. (15)). In summary, the parameters ψ_E 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.

VI. 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 which are purposely cast in terms of engine 'design' problems. By emphasizing extreme simplicity in these examples (Rayleigh heat addition, one-dimensional flow, constant specific heats, etc.), fundamental and significant differences in design information which are provided by the two methods are not obscured by complicating issues which can arise in 'real' engine flow-fields. Any method proposed for the evaluation of complex engine flows with real design constraints should certainly be expected to work for exceedingly simple 'model' flows and constraints.

The first example presented in this paper involves the selection of the optimal length

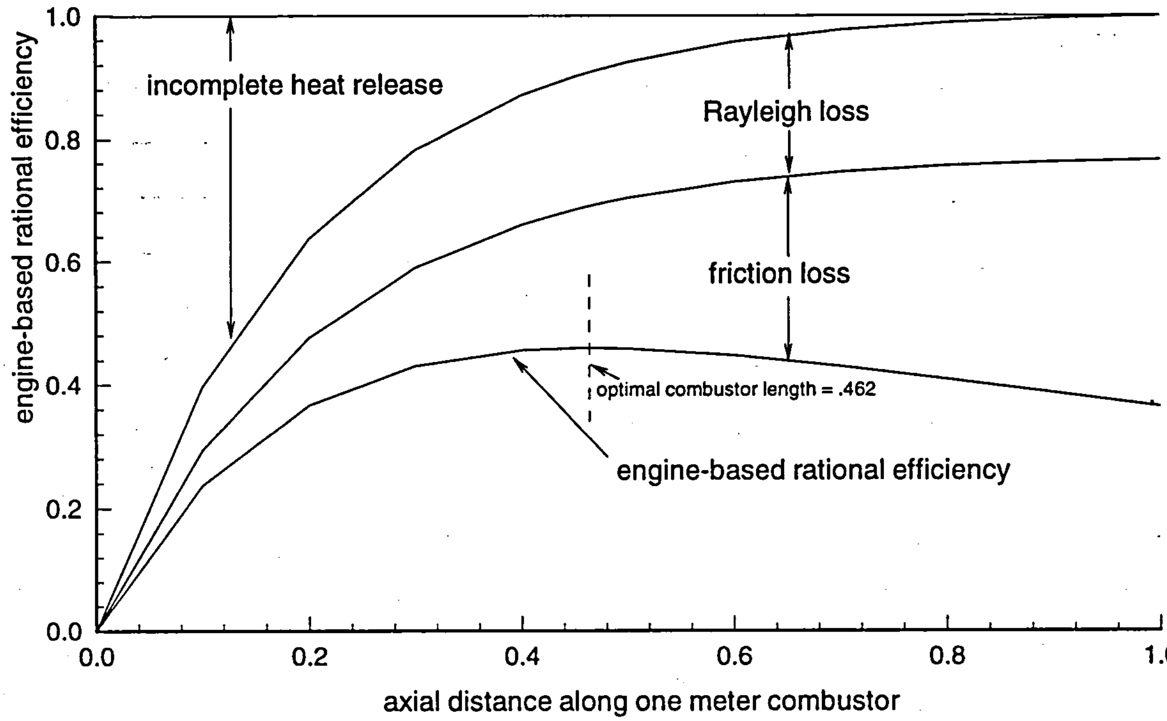


Fig. 21 Engine-based rational efficiency and losses versus axial distance along combustor for simple scramjet with optimal length predicted the same as for the thrust-potential method (compare to Fig. 4)

for a scramjet combustor which 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 exergy method is independent of the degree of expansion and predicts an optimal combustor length which 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 flow-field 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 due to flow irreversibilities is then reviewed; this method allows both the assessment of where and how much thrust is lost within a flow-field due to 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 exergy method to correctly identify the component (or flow region) which has the largest true performance loss due to a particular loss mechanism. Also shown is the close relationship between the engine effectiveness and the overall engine efficiency.

In order to explain the differing results obtained when using exergy and thrust methods, the conventionally defined exergy and the engine thrust are derived, compared and related from a basic thermodynamic and fluid dynamic standpoint. The exergy definition is shown to include non-engine wake processes; analytically and physically it is a closed-cycle quantity which does not account for the open-cycle nature of a Brayton-cycle aerospace engine. As a result, it underpredicts the effect of losses and fails to correctly identify the engine location with which the losses are associated. Finally, the last section in the body of this paper 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 which is inevitably unavailable to the engine. This lost work is due to 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 almost identical to the results obtained using the thrust-based method. This investigation should serve to unify the thrust-based and exergy-based methods and should satisfactorily address long-standing concerns about the use of exergy methods for the analysis of aerospace engines.

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This investigation summarizes a comparative study of two high-speed engine performance assessment techniques based on exergy (available work) and thrust-potential (thrust availability). Simple flow-fields utilizing Rayleigh heat addition and one-dimensional flow with friction are used to demonstrate the fundamental inability of conventional exergy techniques to predict engine component performance, aid in component design, or accurately assess flow losses. The use of the thrust-based method on these same examples demonstrates its ability to yield useful information in all these categories. Exergy and thrust are related and discussed from the stand-point of their fundamental thermodynamic and fluid dynamic definitions in order to explain the differences in information obtained using the two methods. The conventional definition of exergy is shown to include work which is inherently unavailable to an aerospace Brayton engine. An engine-based exergy is then developed which accurately accounts for this inherently unavailabe work; performance parameters based on this quantity are then shown to yield design and loss information equivalent to the thrust-based method.

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