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Thrust Losses in Hypersonic Engines Part 1: Methodology

D. W. Riggins*
University of Missouri–Rolla, Rolla, Missouri 65409
C. R. McClinton†
NASA Langley Research Center, Hampton, Virginia 23681
and
P. H. Vitt‡
Analytical Services and Materials, Hampton, Virginia 23666

Expressions for the thrust losses of a scramjet engine are developed in terms of irreversible entropy increases and the degree of incomplete combustion. A method is developed that allows the calculation of the lost engine thrust or thrust potential caused by different loss mechanisms within a given flowfield. This method allows the performance-based assessment of the trade between mixing enhancement and resultant increased flow losses in scramjet combustors. An engine effectiveness parameter for use in optimization of engine components is defined in terms of thrust losses.

Nomenclature

A = area, cross sectional
AR = area ratio for expansion
C = wetted perimeter of engine at given station
C_f = skin friction coefficient
C_{pi} = specific heat for ith species
F = thrust force, axial
LW = lost thrust work per unit mass
$\dot{m}$ = mass flow rate
P = pressure
R = gas constant
R_v = viscous force
ST = stream thrust, $\dot{m}u + PA$
s = entropy per unit mass
T = temperature
u = velocity
ΔQ = heat interaction
δq = differential heat interaction per unit mass
η_c = energy-based combustion efficiency
η_{ee} = engine effectiveness
ν = specific volume
ρ = density
τ_w = wall shear stress

Subscripts
comp = complete combustion, $\eta_c = 1$
diff = complete–incomplete, parameter
e = nozzle exit
ei = ideal engine nozzle exit, reversible, complete combustion
er = reversible engine nozzle exit, or actual nozzle exit flow expanded to equivalent stream thrust
f = flight condition
incomp = incomplete combustion, $\eta_c < 1$
irr = irreversible
rev = reversible

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*Associate Professor, Department of Mechanical and Aerospace Engineering. Member AIAA.
†Head, Numerical Analysis Office. Member AIAA.
‡Research Engineer. Member AIAA.

Introduction

THE accurate assessment of flow losses and their impact on overall hypersonic vehicle performance is of critical importance in scramjet engine design and evaluation. The analysis in this paper develops an analytical expression for the thrust work losses of a scramjet engine that are caused by irreversibilities and incomplete combustion. This is done in terms of irreversible flow losses and reductions from ideal and complete heat addition or combustion. Flow losses are defined here as increases in irreversible entropy (with attendant reductions in vehicle thrust); these entropy gains are caused by 1) shocks, 2) friction/viscous effects, 3) heat diffusion, 4) Rayleigh losses (caused by heat addition at finite Mach number), 5) fuel–air mixing, and 6) nonequilibrium kinetics. A scramjet engine is an open Brayton cycle device in which gas expansion processes are used to develop thrust. Hence, the ability of the engine to develop thrust efficiently is the ultimate measure of engine performance.[1] Individual components such as combustors and nozzles must be assessed by their contributions to the efficient achievement of overall engine thrust. However, an upstream component with high losses (such as the inlet) may provide a combustor entrance flowfield that interacts productively with the fuel, thus resulting in an overall increase in engine efficiency over that obtained by an inlet with less losses. This design difficulty (or opportunity) inevitably affects all scramjet performance analysis methods and can be addressed only by appropriately computing or measuring the entire engine flowfield, hence, capturing component interactions.

All proposed methods for evaluating scramjet engine performance at high Mach numbers (including exergy-based methods)[2] must ultimately define an engine efficiency whose numerator is vehicle thrust, or thrust work delivered to the vehicle. Exergy, or work availability, is defined as the maximum reversible work that 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. Because, in part, of the open nature of the Brayton cycle, it is not sufficient to examine the loss in exergy across the engine (referenced from the ambient conditions) to assess engine performance. Specifically, it is that portion of the exergy that has been actually realized as useful thrust work that determines the engine performance. The final propulsive figure of merit should be directly related to the fraction of thrust power lost because of irreversibilities as measured from the ideal (best available) thrust power without losses. A comparative ideal engine, by definition, involves reversible compression of the incoming flow to zero Mach number, ideal (reversible) and complete heat release, and finally a reversible expansion process to some exit condition defined by a fixed area ratio (i.e., related to a design engine). Additional expansion of the ideal engine nozzle exit flow to a reference condition (such as ambient pressure) may be utilized in the definition of an engine effectiveness parameter. Although the ideal engine is impossible to build, the thrust power provided by such a conceptual engine provides a logical denominator of a true second-law based engine thrust effectiveness or efficiency. This effectiveness is, in fact, an extension of the so-called combustor effectiveness,[1,3] which is readily extended to the engine as a whole, or to any of its components.

The method developed in this investigation for the evaluation of the thrust losses caused by various loss mechanisms is based upon the premise that the lost thrust work as measured from that of the reversible engine is recoverable (and, hence, is able to be quantified) by an additional isentropic expansion of the actual nozzle exit flowfield. This technique is used only as an analytical procedure for the determination of thrust losses within a given flow. In this investigation, the additional expansion necessary to recover the lost thrust work is derived from first principles in terms of irreversible entropy gains. This method, when correctly implemented, yields consistent results for coupled losses as well as uncoupled losses, i.e., the lost thrust contributions sum exactly to the difference between the thrust provided by the reversible flowfield and the thrust provided by the actual flowfield. This condition for consistency is vital to any meaningful understanding of the performance losses in a real flow that has coupled (concurrent) loss mechanisms. It is not adequate to examine individual losses and engine performance by simply eliminating a single loss mechanism within a simulation (e.g., by eliminating wall friction in a cycle–code study), because of the coupling influence of upstream losses on downstream losses. The approach taken in this work fully accounts for coupling while allowing the exact analytical calculation of the effects of individual loss mechanisms within a given flowfield on the vehicle thrust performance. In addition, the analysis is completely general; it makes no assumptions or requirements concerning the type of combustion in the actual engine (i.e., no assumption of constant-pressure heat addition or any other similar restriction is necessary). Furthermore, there is no unrealistic requirement that the actual nozzle be fully expanded to ambient pressure. Such assumptions, which are very often used in analytical studies, are not generally representative of actual scramjet designs.

The most productive approaches to engine performance evaluation have been based on energy/work availability analysis. Builder[4] defined the overall cycle efficiency for an aerospace engine in terms of engine thrust power as a fraction of the energy input into the system. Other early work includes that of Lewis,[5] who discussed and clarified the second-law relationships in the propulsive efficiency definition for turbojet and turbofan engines. Both of these investigations used vehicle thrust as the natural measure of efficiency, although both assumed matched pressure at the nozzle exit (exit pressure equal to ambient pressure). Standard works on exergy include that of Ahern[6] and Szargut et al.[7] The latter reference includes a discussion of exergy methods applied to jet propulsion. More recently, Czysz and Murthy[2] presented a review of available energy concepts for high-speed flight propulsion systems. This has been followed by a related investigation by Murthy.[8] Riggins et al.[1] performed a computational investigation in which they utilized the conventional combustor effectiveness concept, i.e., that the available and useful propulsive work at any point in the flow is considered to be the thrust work obtainable by isentropic expansion to some reference condition (either the ambient pressure or a fixed area ratio). This parameter, identified variously as the thrust potential, thrust work potential, or thrust availability, is written as follows:

Thrust work potential:

$$\left[\int_e (\rho u^2 + P)\, \mathrm{d}A - \int_i (\rho u^2 + P)\, \mathrm{d}A\right] \frac{U_f}{\rho u A} \tag{1}$$

where the second integral is the stream thrust at the entrance to the engine (or the component being analyzed), the first integral is the expanded stream thrust for the station of interest, U_f is the flight velocity, and the denominator is the mass flow rate. Thrust potential and thrust work potential are related directly through U_f, and they are often interchangeably designated (depending on the context) as the thrust potential. This parameter is extensively used in this work and is shown to be directly linked to the ideal (reversible) engine thrust via irreversible flow losses. In addition, a raw (exit) stream thrust potential can also be defined for a given (fixed) engine inflow. The analysis presented in this article enables the rigorous separation and identification of various thrust losses caused by individual loss mechanisms, in terms of thrust potential.

Thrust Work of Scramjet Engines

The following analysis assumes quasi-one-dimensional flow through a scramjet engine. Three-dimensional flows must be appropriately one dimensionalized for parametric performance evaluations; this analysis can then be used for analyzing multidimensional numerical flowfields.[9] The engine station numbering for both actual and ideal engines is shown in Fig. 1. Note that Δs_{rev} (the entropy associated with the reversible transfer of heat) occurs only when there is heat transferred across the combustor boundary and corresponds to wall heat transfer in a real engine. However, this term can be quite large in an engine or flow in which Rayleigh heat addition is used to model combustion effects in a real engine.

The differential change in F (i.e., the axial force on the vehicle), for any portion of the engine exposed to the fluid stream, can be written as follows:

$$\mathrm{d}F = P\, \mathrm{d}A - \mathrm{d}R_v \quad \text{(viscous)} \tag{2}$$

where $\mathrm{d}R_v$ (viscous) is the differential drag caused by wall friction. Mass and momentum addition because of fuel injection as well as wall heat transfer are readily incorporated into the results of the following analysis, but are omitted here for simplicity. An expression for the differential gas expansion work per unit mass of the fluid is (note that this is not equal to the differential thrust work), by definition

$$-P\, \mathrm{d}\nu = \frac{P}{\rho}\frac{\mathrm{d}\rho}{\rho} \tag{3}$$

From conservation of mass considerations:

$$\frac{\mathrm{d}\rho}{\rho} + \frac{\mathrm{d}A}{A} + \frac{\mathrm{d}u}{u} = 0 \tag{4}$$

Hence, from Eqs. (3) and (4) and the equation of state $P = \rho RT$

$$RT\left(\frac{\mathrm{d}A}{A} + \frac{\mathrm{d}u}{u}\right) = P\, \mathrm{d}\nu \tag{5}$$

Multiplying the terms in Eq. (5) by U_f/u and rearranging, the following is obtained:

$$\frac{U_f}{u} RT \frac{\mathrm{d}A}{A} = \frac{U_f}{u} P\, \mathrm{d}\nu - RT \frac{\mathrm{d}u}{u}\frac{U_f}{u} \tag{6}$$

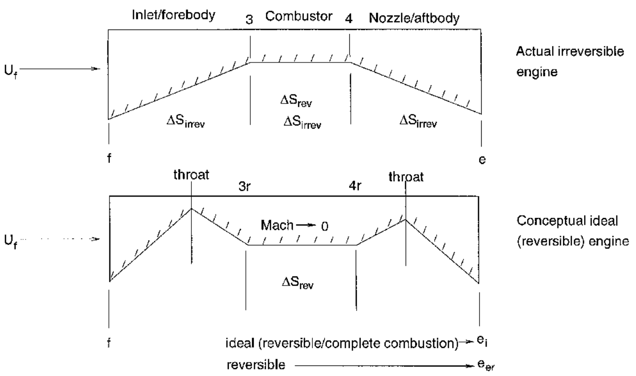

Fig. 1 Schematic of actual irreversible and conceptual ideal engines with engine stations shown.

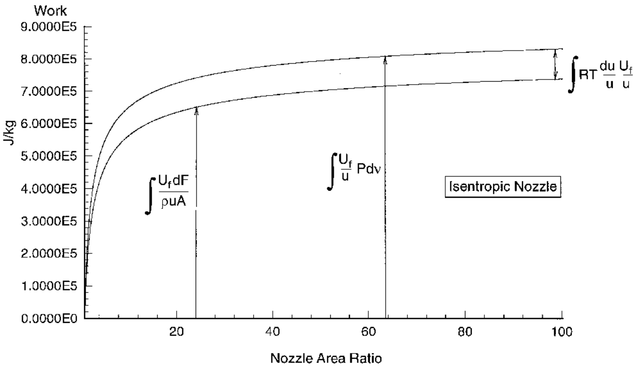

Fig. 2 Nozzle area ratio vs work terms appearing in Eq. (9) for typical isentropic nozzle expansion process.

Now, by multiplying the terms in Eq. (2) by $U_f/\rho u A$, an expression for the differential change in thrust work per unit mass delivered to the vehicle traveling at U_f is obtained:

$$\frac{U_f\,\mathrm{d}F}{\rho u A} = \frac{p}{\rho}\frac{\mathrm{d}A}{A}\frac{U_f}{u} - \frac{U_f}{\rho A u}\,\mathrm{d}R_v \quad \text{(viscous)} \tag{7}$$

Continuing [combining Eqs. (7) and (6) by noting that the left-hand side of Eq. (6) is equal to the first term on the right side of Eq. (7) and by using the equation of state], the following is obtained:

$$\frac{U_f\,\mathrm{d}F}{\rho u A} = \left(\frac{U_f}{u}\right) P\,\mathrm{d}v - RT\frac{\mathrm{d}u}{u}\left(\frac{U_f}{u}\right) - \left(\frac{U_f}{u}\right)\frac{\mathrm{d}R_v \text{ (viscous)}}{\rho A} \tag{8}$$

This equation relates the differential thrust work to the differential gas expansion work in a hypersonic engine. In the absence of friction the last term in Eq. (8) is zero and the change in thrust work is related directly to the expansion work minus a velocity term. In this case, Eq. (8) is rearranged as follows:

$$\left(\frac{U_f}{u}\right) P\,\mathrm{d}v = \frac{U_f P\,\mathrm{d}A}{\rho u A} + RT\frac{\mathrm{d}u}{u}\left(\frac{U_f}{u}\right) \tag{9}$$

Equation (9) can be easily shown to be valid for any gas expansion process (with or without shear). The beneficial thrust work (P dA) term in Eq. (9) is associated with the part of the volumetric gas expansion associated with the thrust in the cross-sectional direction, whereas the velocity (du) term in Eq. (9) is associated with that part of the volumetric gas expansion in the axial (flow) direction. The velocity term in Eq. (9) is generally small with respect to the work term in a high-speed engine, but can nevertheless contribute significantly to the magnitude of thrust (see Fig. 2).

Thrust Work Lost Caused by Irreversibilities

The lost thrust work caused by the presence of irreversibilities in the flow (see Fig. 3) can be derived as follows:

$$LW_{irr} = \int_{T_{er}}^{T_e} \frac{U_f}{u}(T\,\mathrm{d}s_{irr}) \tag{10}$$

By equating mass flow rates and total enthalpies and by using the known ds_{irr} between the actual engine and the differentially more reversible engine, the differential lost thrust work can be computed in terms of ds_{irr}. The lost thrust work between the actual and the completely reversible engine can then be obtained by integrating between T and T_{er} to yield Eq. (10). Alternatively, this expression can also be obtained very simply by describing the reversible engine as exactly equivalent (in terms of thrust delivered to the vehicle) to the actual (irreversible) engine with some effective isentropic increase in nozzle area ratio. This technique of additionally expanding the actual engine flow to recover lost thrust is used in this investigation; it is shown to allow straightforward and effective evaluation of thrust losses caused by irreversibilities. In Eq. (10), T_{er} is the temperature at the exit of the effective nozzle (corresponding to the additional expansion necessary to recover the lost thrust power caused by irreversibilities). The exact amount of additional isentropic expansion of the actual engine flow necessary to recover the lost thrust can be calculated by writing the differential thrust power equation for the effective (additional) nozzle region of the flow as follows:

$$\frac{U_f}{\dot{m}} P\,\mathrm{d}A = \frac{U_f}{u} T\,\mathrm{d}s_{irr} \tag{11}$$

Here, for the additional isentropic nozzle section, d$F = P$ dA (by definition) and the differential thrust work term in Eq. (9) is equated to the differential lost thrust work caused by irreversibilities to recover the lost thrust.

Therefore, from Eq. (11)

$$\frac{\mathrm{d}A}{A} = \frac{\mathrm{d}s_{irr}}{R} \tag{12}$$

Finally, an expression for the area ratio between the actual nozzle exit e and the effective nozzle exit er is arrived at by integrating Eq. (12):

$$A_{er}/A_e = \exp(\Delta s_{irr}/R) \tag{13}$$

Hence, to calculate the thrust lost in the actual engine caused by irreversibilities, the actual nozzle exit flow is additionally

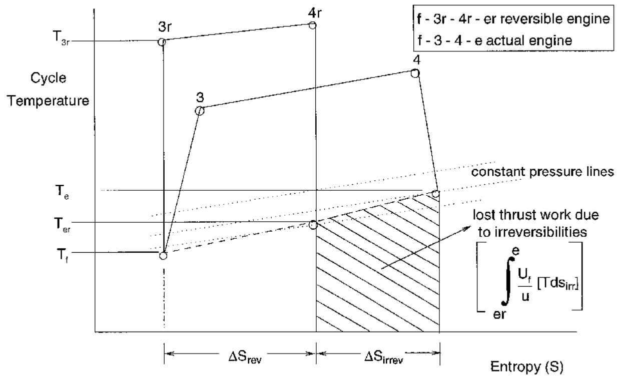

Fig. 3 Temperature–entropy diagram for reversible and actual engines with lost thrust work region illustrated.

isentropically expanded until A_{er} is reached. Note that T_{er} and U_{er} (and, hence, M_{er}) as obtained from this effective additional expansion process are exactly the conditions for the reversible engine expansion to the original physical area ratio. Significantly, the integration path between T_e and T_{er} in Eq. (10) follows exactly the line of constant (fixed) area ratio expansion processes for the same engine with engine irreversibilities progressively removed from rear to front (see Fig. 4); it is not associated with the wake heat rejection process for the actual engine.

Two very simple examples that are used here to illustrate the utility of this method for uncoupled losses are 1) thrust loss caused by a normal shock and 2) thrust loss caused by wall friction in a one-dimensional duct. Figure 5 is a schematic showing the additional nozzle expansion necessary to recover

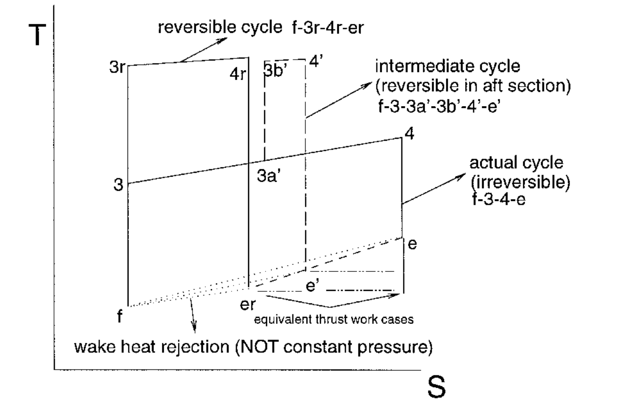

Fig. 4 Temperature–entropy diagram for reversible and actual engines with intermediate engine cycle shown.

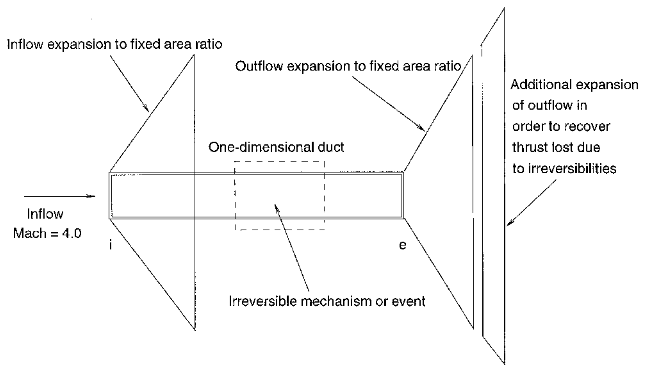

Fig. 5 Schematic of one-dimensional duct with irreversible mechanism with inflow and outflow expansions shown, including additional expansion of outflow necessary to recover lost thrust.

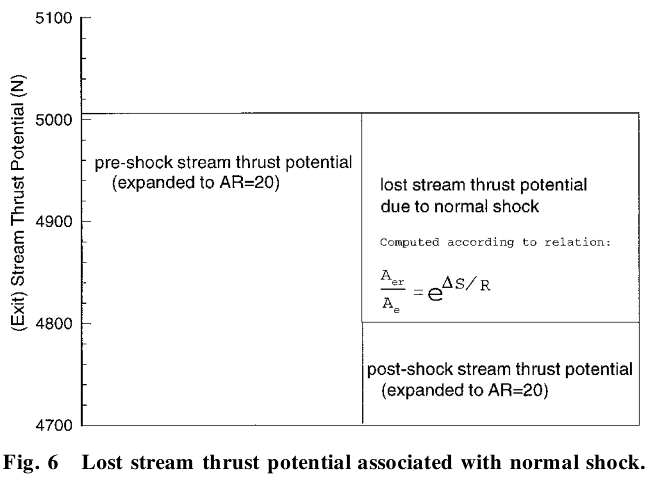

Fig. 6 Lost stream thrust potential associated with normal shock.

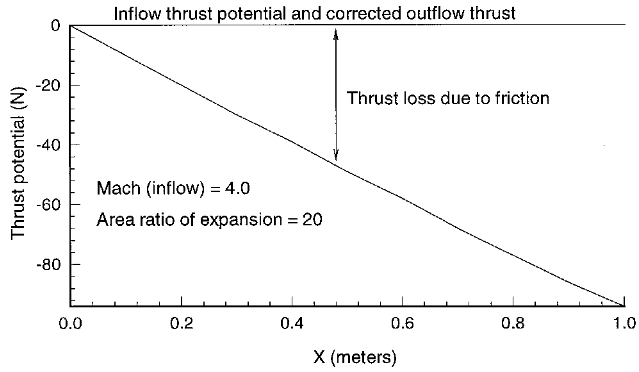

Fig. 7 Lost thrust potential associated with friction.

the thrust lost caused by an arbitrary irreversible event or mechanism in a one-dimensional duct. Figures 6 and 7 show specific results for a normal shock and wall friction, respectively. In both cases, the lost thrust as computed using the method described earlier exactly recovers the original thrust potential (i.e., the ideal) at the inflow of the duct. This recovery is exact regardless of the area ratio of the thrust potential expansion (taken in these examples as 20).

Coupled (concurrent) losses can be treated in a similar fashion providing 1) a differential description of the irreversible entropy gains throughout the flow is provided and 2) downstream flow losses do not significantly affect upstream losses. The latter assumption is generally used, even in low-speed gas turbine engines. Note that Δs_{irr} in Eq. (13) can be considered as the sum of individual coupled irreversible entropy gains, i.e.,

$$\Delta s_{irr} = \Delta s_{Rayleigh} + \Delta s_{shocks} + \Delta s_{friction} + \Delta s_{mix} + \cdots \quad (14)$$

For coupled losses, the exit nozzle is differentially expanded for each separate differential loss, strictly moving from the rear to the front of the engine. This procedure rigorously follows the integration path between T_e and T_{er} as discussed previously, yielding (at any intermediate point) exactly equivalent stream thrust expansion processes between the actual flow with an additional nozzle expansion and the associated flow in the engine that has upstream irreversibilities, but that is reversible in the downstream. Eventually, when T_{er} is reached, the stream thrust of the entirely reversible engine is exactly recovered. This allows the assessment of the specific thrust losses at any given point in the flow, which are a result of the corresponding upstream loss mechanisms (for the flowfield under consideration) by the summation of the differential thrust gains associated with each loss mechanism. This process for two coupled losses (loss A and loss B) is illustrated schematically in Fig. 8. A compatible process that yields identical results to this method is to begin with the reversible flow and progressively reduce the nozzle expansion from the given (fixed) nozzle exit by progressively accounting for actual irreversibilities from front to rear. This process simply follows the same integration path in the reverse direction, i.e., from T_{er} to T_e.

Figure 9 illustrates the results of applying this method to a simple problem consisting of airflow in a one-dimensional duct with two coupled loss mechanisms. These losses are manifested by irreversible entropy increases that are due to both finite Mach number heat addition and wall friction. As seen in Fig. 9, heat addition takes place over the first 50 cm of the duct while friction (with $C_f = 0.003$) acts over the entire length of the duct (1 m). Thrust potential vs axial distance is plotted in this figure with the lost thrust contributions from both heat addition and friction shown. These lost thrust contributions, when added to the actual thrust potential, yield exactly the thrust potential of the independently calculated reversible flow (with the same heat addition schedule), i.e., the method is self-

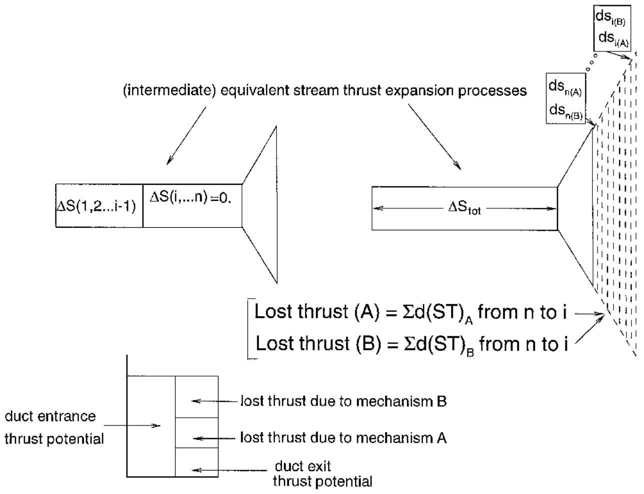

Fig. 8 Schematic of duct with coupled losses (A, B) showing lost thrust calculation procedure for intermediate point in nozzle expansion process.

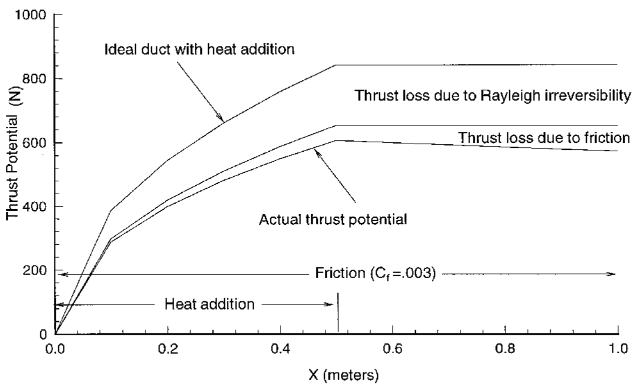

Fig. 9 Thrust potential and losses vs axial distance for flow with coupled Rayleigh and friction losses.

consistent in recovering the thrust potential of the completely reversible flow.

Mixing Enhancement in Hypersonic Engines

Incomplete combustion (i.e., caused by finite rate kinetics or incomplete mixing) also results in a thrust loss from the ideal across the engine. An expression that represents this loss can be developed by examining a simplified T–S diagram for the case of Rayleigh heat addition (Fig. 10) in which the effect of incomplete heat release on the ideal (reversible) case is diagrammed. The differential lost thrust work caused by incomplete heat addition is obtained as

$$\frac{U_f(P\ \mathrm{d}A)}{\dot{m}} = \frac{U_f}{u}(\delta q_{\mathrm{diff}} - T\ \mathrm{d}s_{\mathrm{diff}}) \tag{15}$$

Here, ΔQ_{diff} is the heat actually released into the flow and is equal to $\Delta Q(1 - \eta_c)$, ΔQ is the total heat expended by the vehicle (corresponding to the maximum heating potential of the fuel in a real engine), $\Delta s_{\mathrm{diff}} = \Delta s_{\mathrm{comp}} - \Delta s_{\mathrm{incomp}}$, and η_c is an (energy-based) combustion efficiency mimicking the effect of a true combustion efficiency in an engine with fuel injection followed by downstream mixing-limited chemical reactions. This expression [Eq. (15)] is readily derived by effectively reducing the nozzle area ratio for the ideal (complete heat release) engine until thrust equality is enforced between the ideal engine with complete heat release and the reversible engine with incomplete heat release. Like the method developed for computing thrust losses caused by irreversibilities, this represents only an analytical technique used to calculate the differential thrust loss caused by incomplete heat release. The summation of the lost thrust caused by incomplete heat release across the reversible engine is obtained by the integration of Eq. (15) from er (incomplete) to ei (complete).

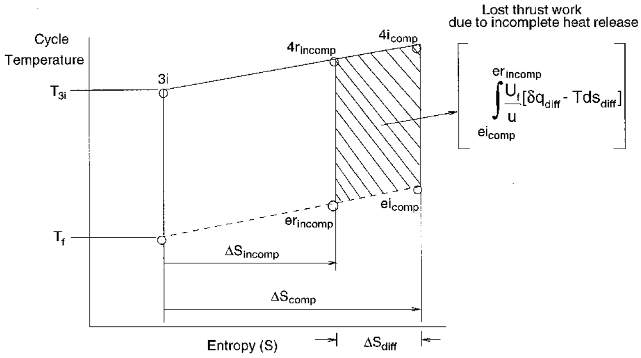

Fig. 10 Temperature–entropy diagram for ideal (complete) and reversible (incomplete) cycles showing effect of incomplete combustion.

Equations (11) and (15) then lead to the following general descriptive relation:

$$LW_{\mathrm{lost}} = f(1 - \eta_c) + g(\Delta s_{\mathrm{irr}}) \tag{16}$$

which describes the net thrust work loss in an actual scramjet engine (LW_{lost}) as the summation of 1) thrust work losses caused by incomplete combustion (f) and 2) thrust work losses caused by irreversibilities (g). The irreversible entropy term (g) in Eq. (16) can be readily subdivided into various loss mechanisms, i.e.,

$$g(\Delta s_{\mathrm{irr}}) = g_1(\Delta s_{\mathrm{Rayleigh}}) + g_2(\Delta s_{\mathrm{shock}}) + \cdots \tag{17}$$

Scramjet mixing enhancement strategies always involve minimizing ΔQ_{diff} [i.e., maximizing η_c or minimizing the function f in Eq. (16)]. However, these methods also always entail the generation of irreversibilities (increasing Δs_{irr}, hence, increasing the function g) to achieve this additional fuel–air mixing. There is, therefore, a clearly visible trade between additional mixing and resultant flow losses.[10] This trade is clearly illustrated by Eq. (16). An example of mixing enhancement concepts is found in the numerous studies of the relative performance of swept-sided and straight-sided fuel injector ramps in which sweep is added to the ramp sides to increase the large-scale counter-rotating spillage-induced flow vortices.[11,12] Although the sweep has been shown to increase both vorticity and subsequent mixing, there is also an attendant increase in the irreversible entropy gain (i.e., from the stronger bow shock from the swept-sided ramp). Equation (16) demonstrates the inevitable second-law issues associated with mixing enhancement techniques.

Thrust Losses in a Scramjet Engine (Cycle Code Results)

To demonstrate the method developed in this investigation for the analysis of thrust losses in a realistic engine flowfield, a cycle analysis code with detailed second-law accounting has been written. This code solves the following one-dimensional governing equations for flow in a varying area stream-tube:

$$\frac{\mathrm{d}\rho}{\rho} + \frac{\mathrm{d}u}{u} + \frac{\mathrm{d}A}{A} = 0 \tag{18}$$

$$\frac{\mathrm{d}P}{\rho} + u\ \mathrm{d}u = \frac{-\tau_w}{\rho}\left(\frac{C}{A}\right)\mathrm{d}x \tag{19}$$

$$\mathrm{d}\left\{\left[\sum_{i=1}^{NCS} \alpha_i \left(h_{oi} + \int_{T_{\mathrm{Ref}}}^{T} C_{pi}\, \mathrm{d}T\right) + \frac{u^2}{2}\right] \dot{m}\right\} = \delta q \tag{20}$$

$$P = \rho R T \tag{21}$$

Equations (18–21) represent the conservation of mass, the axial momentum equation, the energy equation, and the gas equation of state, respectively. R in Eq. (21) is the mixture gas constant, NCS is the number of chemical species in the mixture, and α_i is the mass fraction of species i.

τ_w is modeled using C_f, i.e.,

$$\tau_w = \tfrac{1}{2}\rho u^2 C_f \tag{22}$$

The specific heats for the individual species are modeled utilizing polynomials such that

$$(C_{pi}/R_i) = a_i + b_i T + c_i T^2 + d_i T^3 + e_i T^4 \tag{23}$$

where the coefficients a_i, b_i, c_i, d_i, and e_i are obtained from thermodynamic curve fits.[13] The Reynolds analogy is used for convective wall heat transfer. Finite rate reaction is modeled using a simple global one-reaction H_2–O_2 model

$$H_2 + \tfrac{1}{2}O_2 \rightleftarrows H_2O \tag{24}$$

Note that this formulation of equations is typical of many working cycle codes and is presented here only to demonstrate that the thrust modeling methods previously described perform well for complex (generalized) flows with variable specific heats, multiple species, nonequilibrium kinetics, fuel injection, and mixing, etc.

Figure 11 is a schematic of the geometry of a generic hypersonic engine configuration with inlet/forebody, combustor, and nozzle/aftbody. The flight Mach number is 12 with ambient conditions and injection conditions as indicated. The inlet capture area and nozzle expansion area ratio are equated for simplicity in this example. The flowfield for this engine is simulated in this investigation only to demonstrate the thrust modeling techniques developed in this investigation. Hence, the geometry and flight conditions are arbitrary.

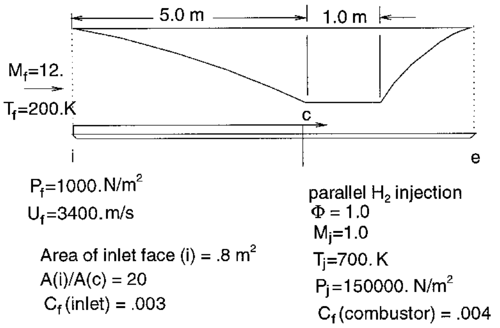

Fig. 11 Schematic of generic hypersonic engine and conditions.

The actual thrust potential for this particular configuration, the various lost thrust increments caused by individual loss mechanisms, and the ideal thrust potential are plotted in Fig. 12. The thrust potential is examined only over the length of the inlet and combustor for this study. In the inlet, the thrust loss is a result of two effects: 1) wall heat removal and 2) wall friction. The downstream-directed fuel injection provides a significant and instantaneous boost in thrust. In the combustor itself, thrust losses are caused by friction (further subdivided into upstream or inlet friction losses and combustor friction losses), fuel injection/mixing losses, nonequilibrium reaction, wall cooling, and incomplete combustion. In the first 50 cm of the combustor, the actual thrust potential increases because of reaction, but in the latter half of the combustor (0.5–1.0 m), friction and wall cooling predominate and the thrust potential declines. Again, as in the simple examples shown earlier, when the thrust losses caused by irreversibilities are added to the actual thrust potential, the sum recovers exactly the corresponding reversible flow (independently computed with the same heat removal from the walls and chemical species distribution as in the actual flow). The individual lost thrust values as a result of individual irreversibilities are unique at a given axial station in Fig. 12; one can interchange the loss ordering (and, hence, the appearance of the figure), but will still have exactly the same values for all lost thrusts caused by specific loss mechanisms. The method developed in this article accounts for the coupling that exists between flow losses, i.e., the losses are dependent but are separately (and uniquely) able to be quantified for a given flowfield for which a complete differential description is available. The sum of the lost thrust increments caused by all irreversibilities (region A + B + C + D) is directly related to the function g in Eq. (16), whereas region E is directly related to the function f (the thrust loss caused by incomplete combustion) in the same equation.

Engine Effectiveness Parameter

The foregoing analysis and examples lead naturally to a logical parameter for the evaluation of scramjet engine and engine component performance. This parameter, or permutations of it, has been previously designated the combustor effectiveness in the literature[1,3] (including work done in the 1950s).[14] In this paper, an overall engine thrust effectiveness is proposed as follows:

$$\eta_{ee} = \frac{\text{Actual net thrust across engine}}{\text{Ideal engine net thrust (expanded to same fixed area ratio)}} \tag{25}$$

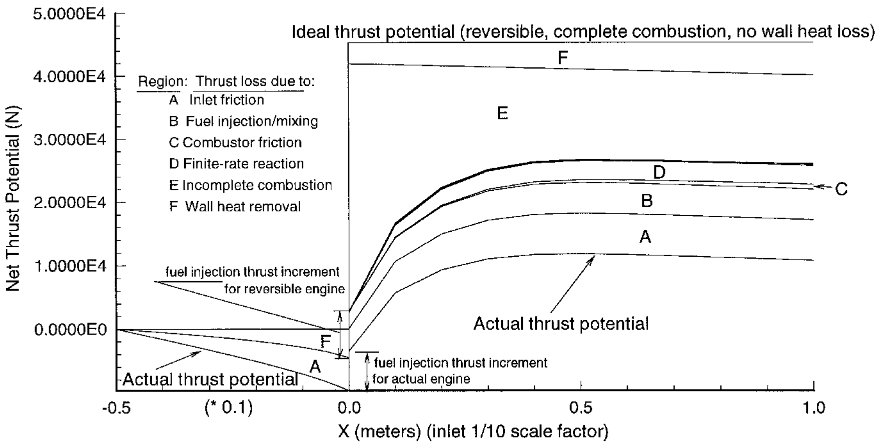

Fig. 12 Thrust potential and various losses vs axial distance for engine flowfield computed using cycle code.

This can be written (evaluated over the entire engine) as

$$\eta_{ee} = \frac{\text{Actual net thrust across engine}}{\text{Actual net thrust across engine} + \Delta F_{irr} + \Delta F_{incomp}} \tag{26}$$

The denominator in Eqs. (25) and (26) (the ideal net thrust) is defined in an identical fashion as in previous sections; for meaningful analysis of a thermally balanced engine, the ideal engine should be computed with the same wall heat-removal as experienced by the actual engine. Note that the denominator in the engine effectiveness could include if desired, additional thrust caused by additional isentropic expansion of the ideal engine nozzle exit flow to the ambient pressure. This would make the denominator of the engine effectiveness independent of the engine exit area. Note also that the reversible engine net thrust can be recovered readily by additional expansion of the actual nozzle exit flow as suggested in the previous sections; this expansion defines exactly the lost thrust power caused by irreversibilities. The process developed in this investigation eliminates the need to actually compute a reversible high-enthalpy flowfield (based on slowing the flow reversibly to Mach zero before heat addition) to study the effect of irreversibilities. The engine effectiveness parameter as defined in Eq. (26) can be used in a straightforward manner to evaluate and compare scramjet engine thrust effectiveness. In addition, the basic concept of engine effectiveness can be directly extended to any individual engine component. The engine effectiveness concept, like the thrust potential on which it is directly based, is a rigorous second-law based efficiency.

Summary

This investigation addresses a crucial issue in ramjet/scramjet combustor/engine flow path evaluation. The relationships between engine thrust and engine thrust losses caused by incomplete burning and irreversible flow losses are clearly defined and illustrated.

The method developed in this work enables the separation and determination of the magnitudes of the various thrust losses caused by the various flow loss mechanisms within a given flowfield. It is derived from thermodynamic and fluid-dynamic first principles and is shown to be consistent for both simple and complex flows with coupled losses. The design of efficient and mission-optimized hypersonic engines requires detailed understanding of performance loss mechanisms in high-speed internal flows; this investigation develops and evaluates a technique contributing to this understanding. The technique is applicable to design efforts ranging from parametric studies using one-dimensional cycle code decks to detailed three-dimensional computational fluid dynamics simulations.

The evaluation of mixing enhancement strategies must take into account the performance loss caused by increased flow losses as described in this paper. This work also demonstrates that the thrust potential method provides a rigorous spatial measure of engine performance potential. This method is based upon the measurement of the true thrust-based performance potential of the flow at any engine station by expansion to the exit area associated with the engine. The analysis and results described in this investigation justify fully the use of thrust availability techniques in the evaluation of injection strategies and in parametric engine design trade studies.

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