Optimal Architecture for Efficient Steady-Flow Engines

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Introduction

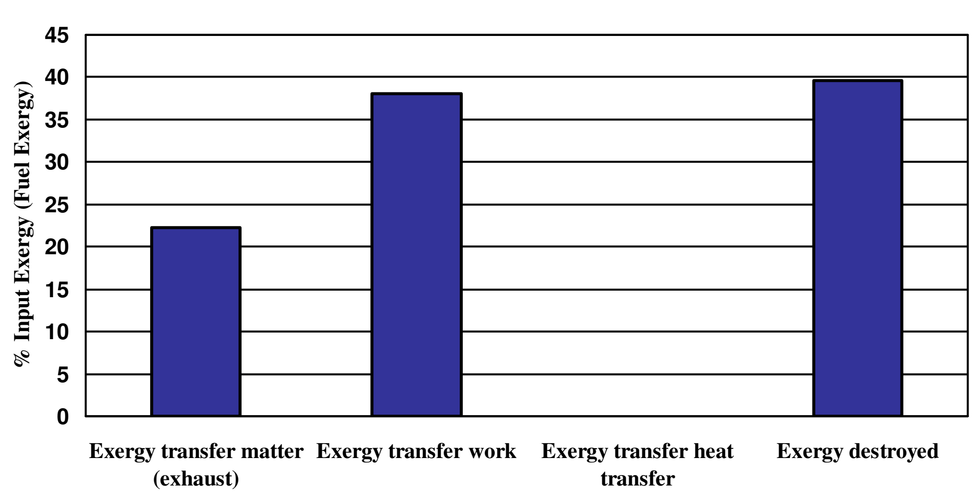
Gas turbine engines are ubiquitous in electrical power generation and aviation. A large variety of simple, regenerative and combined cycles exist in operation and many more are being researched. Parametric thermodynamic studies, and thermo-economical optimization studies for these cycles are available in the literature.

However, these studies have two major drawbacks:

- These studies employ a top-down approach to increasing efficiency i.e., a cycle is assumed and its efficiency is improved by changing the operating parameters.
- Combustion is modeled as a heat transfer process from a heat source, and combustion irreversibility is replaced by an obscure and unphysical quantity "heat-resistance".

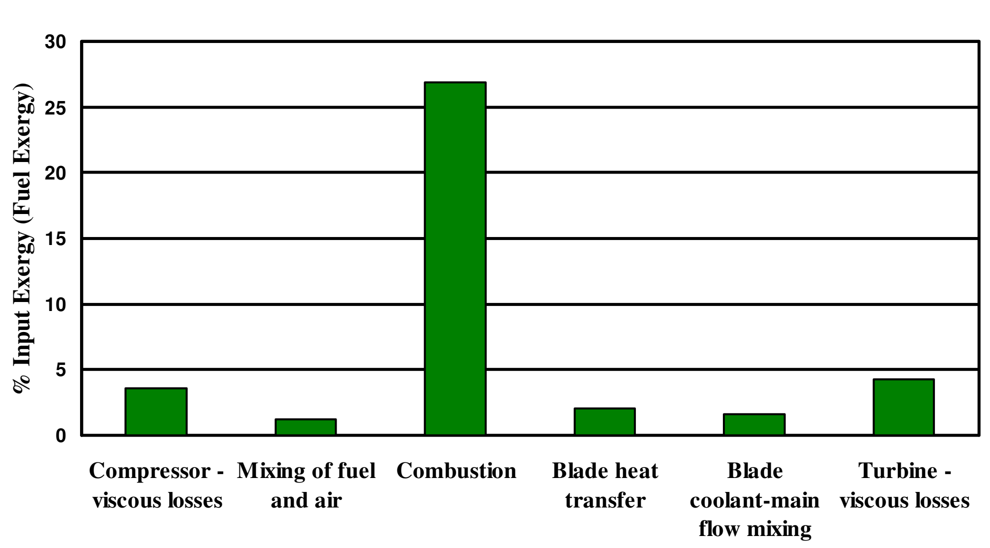
A fundamental approach is, therefore, needed to obtain an optimal engine cycle and engine architecture from thermodynamic first principles, that minimizes the total irreversibility and maximizes the efficiency of gas turbine engines.

The maximum work potential of an energy resource (fuel) is its exergy. Exergy is destroyed due to entropy generation, i.e. irreversibility. A blade-cooled, simple-cycle engine with a pressure ratio of 18:1 loses approximately 40% of its work potential due to irreversibility.



Major sources of irreversibility in any simple-cycle gas-turbine engine are:

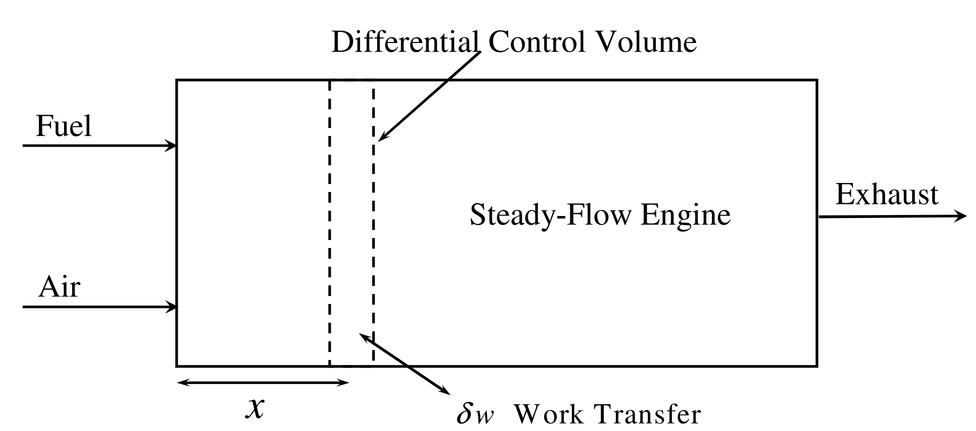
- Combustion (chemical reaction)
- Viscous dissipation of kinetic energy in turbomachinery
- Mixing of fuel and air



This study aims to arrive at an engine cycle and architecture that has the lowest irreversibilities of any conceivable cycle. This approach also uncovers the thermodynamic principles key to efficiency maximization that will be useful in anticipating effects of various architecture modifications. Currently, results have been obtained for the class of simple-cycle, gas-turbine engines. Work is in progress for the extension of this concept to regenerative cycles.

Model Description

The engine is modeled as a series of quasi-one-dimensional, differential control volumes. Each control volume involves some control action (with or without work transfer) and is associated with the corresponding architectural element e.g., a differential compressor, nozzle, mixer etc. The fuel and air (un-mixed) enter the engine through the entry plane and their thermodynamic state is changed by the control action in each of these control volumes. The optimal engine is an optimal sequence of control actions such that entropy generation is minimized.



The following assumptions are made:

- Fast mixing and homogenous combustion
- No heat transfer (adiabatic)
- Local thermodynamic equilibrium exists at every location in the engine

The reacting mixture can be characterized at any location by its thermodynamic state $s(h(x), P(x), \mathbf{Y}(x))$.

The engine can be visualized as a path in the $s(h, P, \mathbf{Y})$ thermodynamic state-space from the reactant state $s_i(h_i, P_i, \mathbf{Y}_i)$ to the product state $s_f(h_f, P_f, \mathbf{Y}_f)$. The optimal path – the one that minimizes entropy generation – is the optimal engine.

Optimal Control Problem

Entropy generation in a control volume is given by :

$$ds = \delta s_{gen} = \frac{v dP(\alpha-1)}{T} + \frac{d(k.e.)(\beta-1)}{T} - \sum_j \frac{(\mu_j d\mathbf{Y}_j)}{M_j T}$$

α, β: device irreversibility factors based on second-law efficiencies

While the change in the mixture composition ($d\mathbf{Y}j$) is governed by the chemical kinetics, pressure and kinetic-energy are the control variables. Accordingly, the permissible set of controls, and the associated architectural elements are:

Control	Device	α	β
$dP>0, d(k.e.)=0$	Compressor	$1/\eta_C$	1
$dP<0, d(k.e.)=0$	Turbine	η_T	1
$dP=0, d(k.e.)>0$	Accelerator	1	$1/\eta_{Ac}$
$dP=0, d(k.e.)<0$	Decelerator	1	η_{Dc}
$dP>0, d(k.e.)<0$	Diffuser	1	η_D
$dP<0, d(k.e.)>0$	Nozzle	η_N	1

The optimal engine is thus, a solution of the following optimal control problem:

$$\min s_{gen} = \int_i^f ds\left(h, P, \mathbf{Y}, \frac{dP}{dt}, \frac{d(k.e.)}{dt}\right) \quad \text{(Cost function)}$$

System Dynamics & Constraints:

$$\dot{h} = v(h,P,Y)\frac{dP}{dt}\alpha + \frac{d(k.e.)}{dt}(\beta-1) \quad \text{(I Law of thermodynamics)}$$

$$\dot{\mathbf{Y}}_j = f_j(h,P,Y) \quad \text{(Reaction kinetics)}$$

$$|\dot{P}| \le \dot{P}_{max} \quad \text{(Bounded rate of change of pressure)}$$

$$\left|\frac{d(k.e.)}{dt}\right| \le \frac{d(k.e.)}{dt}_{max} \quad \text{(Bounded rate of change in k.e.)}$$

$$P_f - P_0 < \delta \quad \text{(Pressure at engine exit = } P_{atm}\text{)}$$

$$\xi(t_f) = 1 - \frac{(s_{eq}(h,P,Y_{eq}) - s(h,P,Y))}{(s_{eq,i}(h,P,Y_{eq,i}) - s_i(h,P,Y))} \ge \xi_0 \quad \text{(Extent of reaction)}$$

Optimal Engine Cycle

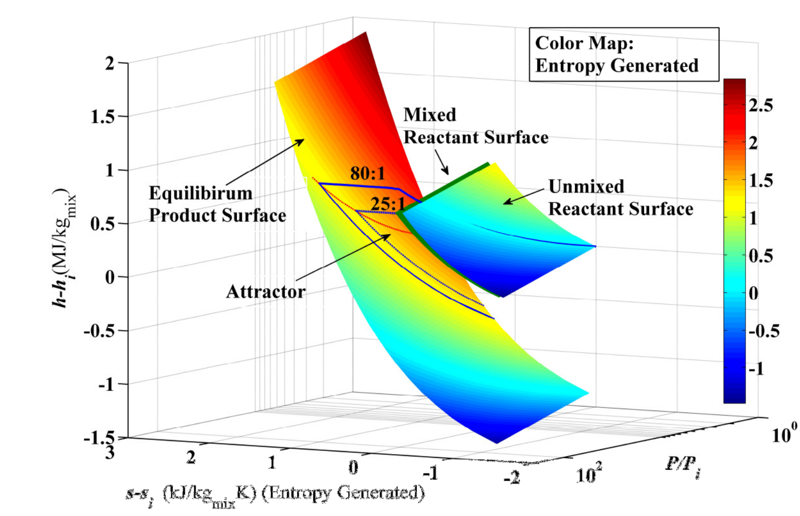
Optimal cycle

- Compression of unmixed reactants to the maximum possible mixing pressure
- Mixing of reactants; initiating the start of combustion
- Compression during combustion until the "limiting switching point" for compression is reached
- No control action (neither compression nor expansion) until combustion is complete
- Work extraction by expansion

At any location in the engine the minimum-irreversibility, pressure limit P^* must not be exceeded.

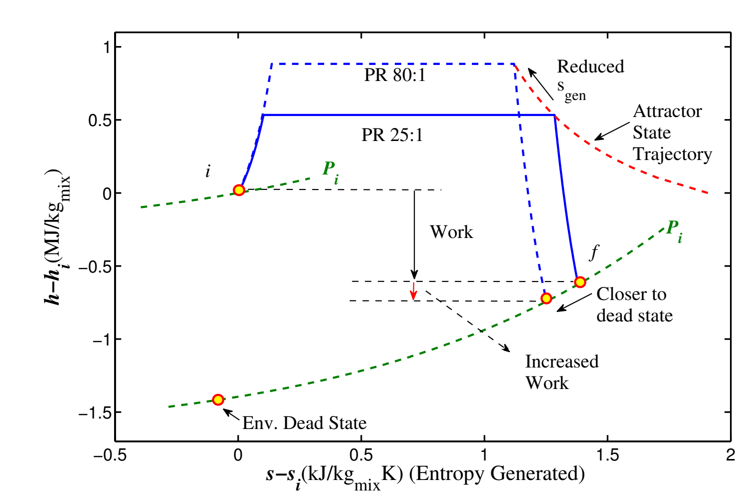
Equilibrium attractor states

If no control action is taken at any location, the reactant mixture will approach the constant $h-P$ chemical equilibrium due to combustion. This equilibrium state is the "attractor state" on the equilibrium product surface.

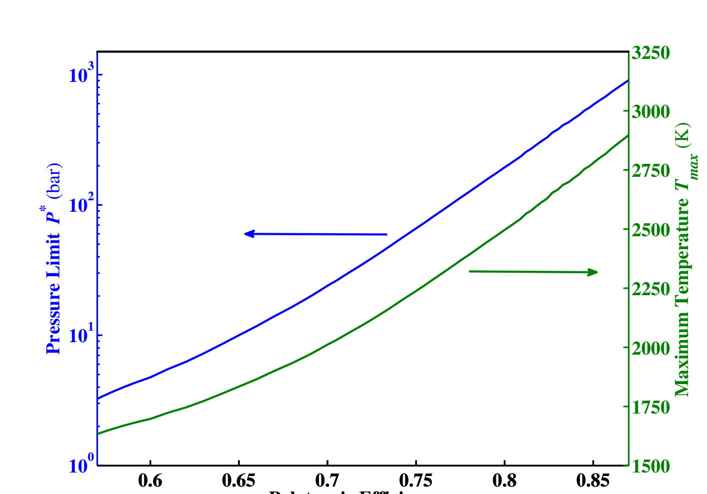


Thermodynamics of the optimal cycle

- Irreversibility occurring prior to completion of combustion can be reduced by employing control actions that steer the system towards lower entropy.
- Taking the system to the highest possible enthalpy state prior to completion of combustion reduces the irreversibility mentioned above.



- The entropy of mixing of the reactants is negligible compared to that of combustion and is not sensitive to changes in the reactant state.
- Irreversibility during work extraction increases with pressure ratio, opposing the requirement set by combustion irreversibility. Minimum-irreversibility pressure limit P^* exists for any cycle.



Optimal Engine Architecture

The optimal engine must be viewed as a series of differential turbomachinery devices (one for each control volume), that execute the optimal cycle. Each device changes the system state thereby changing the attractor state. Optimal control steers the system towards lower-entropy attractor states.

The trajectory of the attractor states as a function of the control, is given by:

$$ds_{eq} = \frac{dP(v\alpha - v_{eq})}{T_{eq}} + \frac{d(k.e.)(\beta-1)}{T_{eq}} \le 0$$

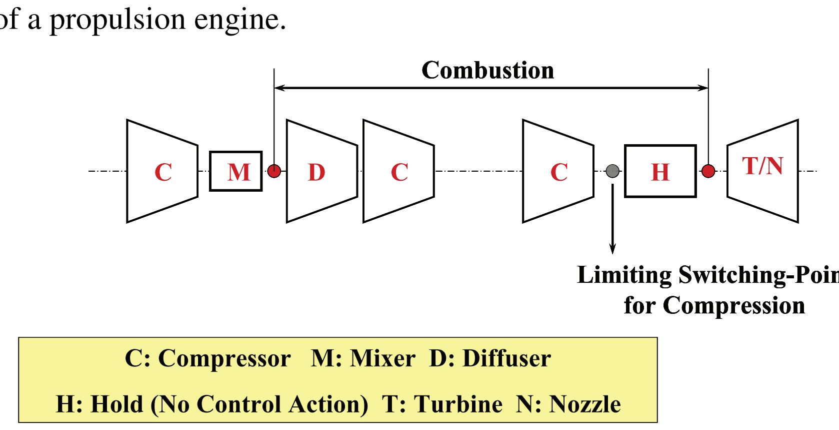
The device that provides the largest negative ds_{eq} must be used at any location in the engine. This establishes some rules for the optimal engine architecture.

Architecture before completion of combustion:

- Accelerator and decelerators (devices changing only kinetic energy but not the pressure) are not permitted in the optimal cycle.
- Compression devices (compressors and diffusers) can be used only at locations where $v\alpha_c \le \beta_c v_{eq}$. The control volume after which no compression device satisfies this criterion is the limiting switching-point for compression.
- Expansion devices (turbines and nozzles) can be used where $v\alpha_E \ge \beta_E v_{eq}$. The control volume before which no expansion device satisfies this criterion is the limiting switching-point for expansion.
- If neither criterion is satisfied, no control action must be taken.

Architecture after complete combustion:

- Work extraction using a turbine for a stationary engine, or a nozzle in the case of a propulsion engine.



The Brayton approximation

- Obtaining a significant pressure rise during combustion would require a very high compression rate.
- Neglecting compression during combustion approximates the optimal cycle to a Brayton cycle.

Conclusions & Future Work

Although the optimal cycle gets approximated to a Brayton cycle for simple-cycle engines, the extreme-state principle uncovered by this approach explains the physics of irreversibility minimization in steady-flow engines. Using this principle, the effect of cycle design modifications like, intercooling, aftercooling, preheating, etc. on engine efficiency, can be predicted easily.

The extreme-state principle also suggests other ways to reduce irreversibility, apart from increasing the pressure ratio. Pre-heating, increasing the equivalence ratio of the reacting mixture and high-enthalpy-stream moderation are some examples. These methods don't increase the work extraction in a simple cycle, but increase the exergy of the exhaust stream. This provides opportunities for increasing cycle efficiency in combined and regenerative cycles. Future work, therefore, involves:

- Extending the optimal-control approach to regenerative engines
- Considering engines with supersonic flow, detonations, shocks, etc. for optimization

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