Optimal Architecture for Efficient Steady-Flow Engines

S. Ramakrishnan, K.-Y. Teh, S.L. Miller, C.F. Edwards

Advanced Energy Systems Laboratory, Department of Mechanical Engineering, Stanford University

Introduction

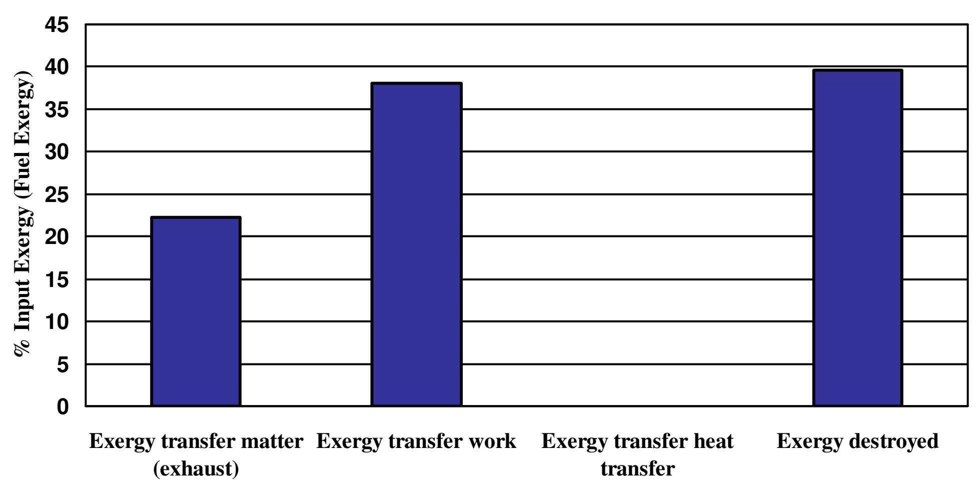
Steady-flow engines are ubiquitous in electrical power generation and aviation. A large variety of simple, regenerative and combined cycles exist in operation and many more are being researched. Parametric thermodynamic studies, and thermo-economic optimization studies for these cycles are available 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 steady-flow engines.

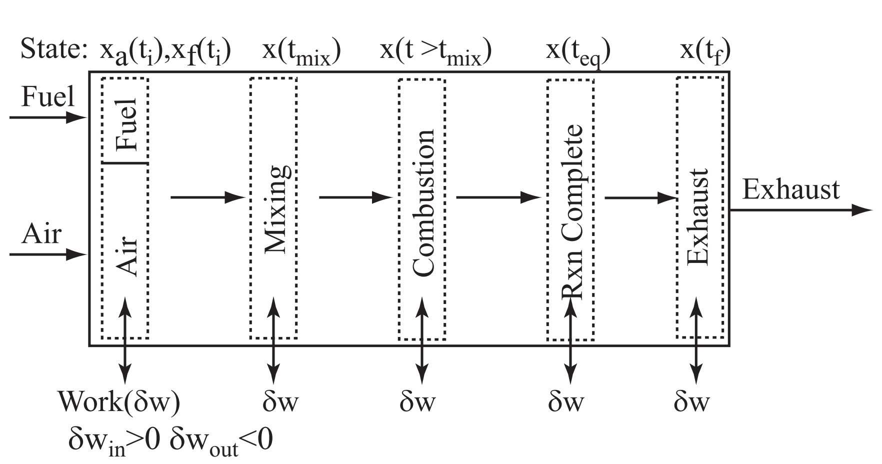
The maximum work potential of an energy resource (fuel) is its exergy. Exergy is destroyed due to entropy generation, i.e., irreversibility. A blade-cooled, simple-cycle engine with a pressure ratio of 18:1 loses approximately 40% of its work potential due to irreversibilities.



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 and propulsion engines. Work is in progress for the extension of this concept to regenerative cycles.

Model Description

The steady-flow engine is modeled as the trajectory of a quasi-one-dimensional, fuel-air, dynamical system in the thermodynamic state-space, as it evolves from unmixed-reactants state to exhaust-products state. The thermodynamic state of the system is defined using the enthalpic representation $x(t) = (h(t), P(t), \mathbf{Y}(t), k.e.(t))$.



Irreversibilities occur in steady-flow engines due to:

- Chemical reactions during combustion
- Non-isentropic transfer of energy as work in turbomachinery
- Dissipation of kinetic energy in nozzles and diffusers
- Mixing of reactants before and/or during combustion.

Optimal Control Formulation

Entropy generated in the system at any location in the engine 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 device polytropic efficiencies

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

Each device represents a permissible way the state of the reacting system can be changed and controlled as it passes through the engine. The action of each device therefore corresponds to a control variable.

$$u(t) = (\dot{P}_c(t), \dot{P}_t(t), \dot{K}_{ac}(t), \dot{K}_{dc}(t), \dot{K}_n(t), \dot{K}_d(t))$$

The minimum-irreversibility, engine cycle corresponds to an optimal control such that the total irreversibility is minimized. This also yields the optimal sequence of the devices that define the optimal engine architecture. This is can be obtained by solving the following optimal control problem:

$\min s_{gen} = s(t_f) - s(t_i)$ (Cost function)

System Dynamics:

$\dot{h} = v(\frac{\dot{P}_c}{\eta_c} + \eta_t \dot{P}) - (\dot{K}_n + \dot{K}_d) + (\frac{1}{\eta_{ac}} - 1)\dot{K}_{ac} + (\eta_{dc} - 1)\dot{K}_{dc}$ (I Law of thermodynamics)

$\dot{P} = \dot{P}_c + \dot{P}_t - \frac{\dot{K}_n}{v\eta_n} - \frac{\eta_d \dot{K}_d}{v}$

$\dot{k}.e. = \dot{K}_n + \dot{K}_d + \dot{K}_{ac} + \dot{K}_{dc}$

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

Constraints:

$\xi(t_f) = 1 - \frac{(s_{eq}(h, P, Y_{eq}) - s(h, P, Y))}{(s_{eq,i}(h, P, Y_{eq,i}) - s_i(h, P, Y))} \geq \xi_0$ (Complete combustion)

$T \leq T_{max}$ (Maximum blade temperature)

$k.e. \geq k.e._{min}$ (Prevention of flow stagnation)

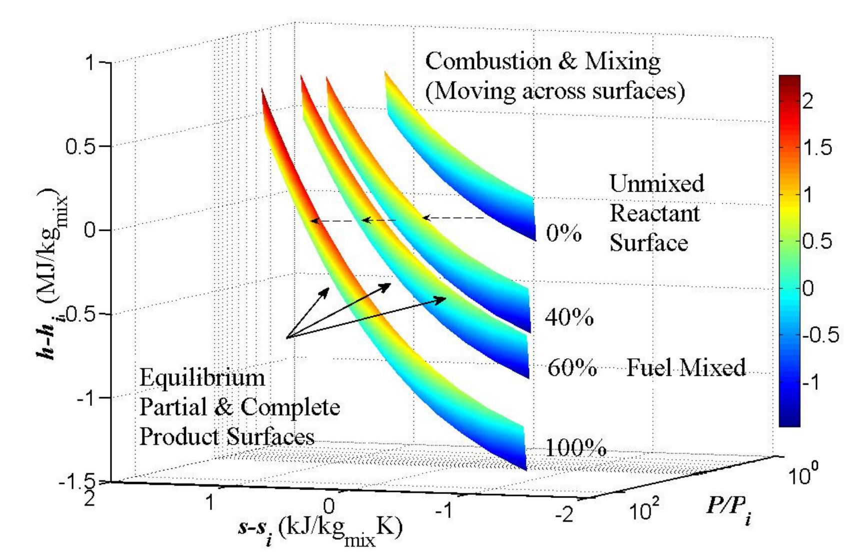
$P \leq P_{max}$ (Maximum pressure)

Exit Conditions:

$P = P_0, k.e. = k.e._0$ (For stationary engines)

$P = P_0, k.e. = k.e._1 >> k.e._0$ (For propulsion engines)

This optimal control problem is solved for engines with premixed, homogenous combustion. The premixed engine can be understood as a trajectory from the unmixed fuel-air surface in the thermodynamic state space (shown in the figure below) to the complete-chemical-equilibrium surface. The system moves directly between the two surfaces. Non-premixed combustion can be modeled as having a multistage mixing-combustion process and can be understood to be passing through partial equilibrium surfaces. As the boundary surfaces are the same, the results for premixed engines can be easily extended to non-premixed engines.



Optimal Stationary Steady-Flow Engine

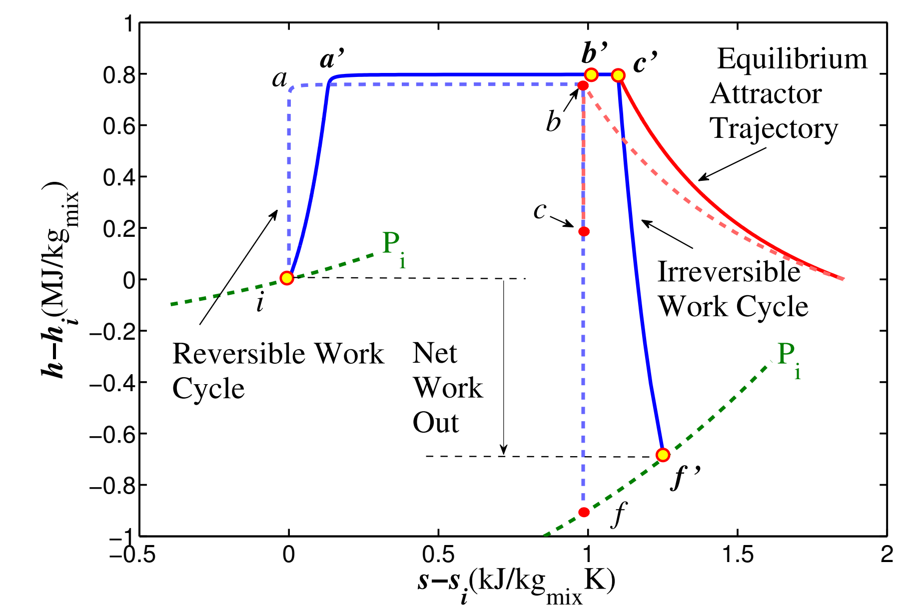
Optimal Premixed Combustion Engines

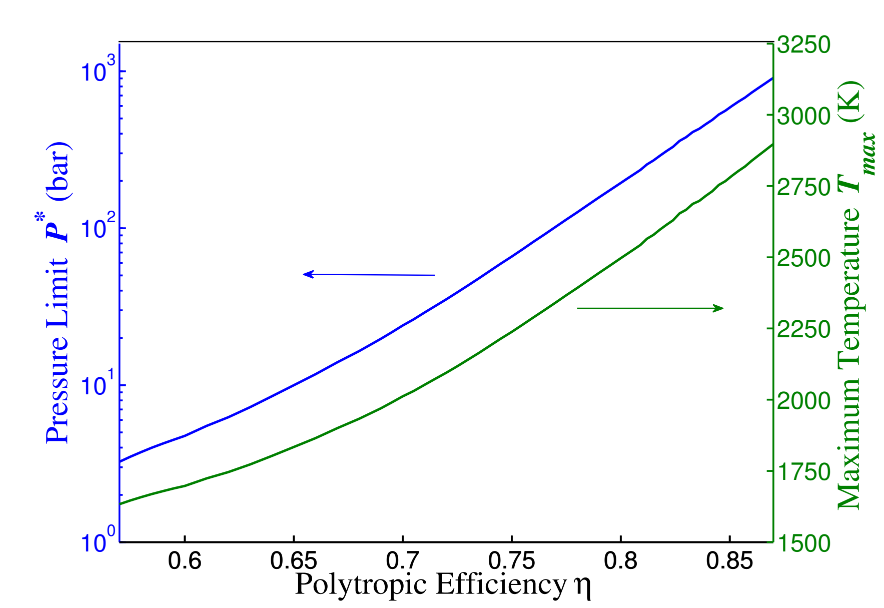
The optimal control problem is solved for premixed homogenous kinetics. The maximum temperature constraint is not considered. The optimal architecture obtained has the following characteristics,

• Combustion irreversibility is minimized by taking the reacting system to high enthalpy states ("extreme states") by compressing and diffusing the kinetic energy before and after auto-ignition (state a' in the figure)

• The presence of device irreversibilities sets an optimal maximum pressure that corresponds to the most efficient engine cycle.

The figures below show the optimal cycle and the variation of optimal pressure with compressor and turbine polytropic efficiencies.





Optimal Non-Premixed Combustion Engines

Mixing irreversibility is an order of magnitude smaller than the other irreversibilities and is not sensitive to state changes. Therefore the optimal control remains the same for non-premixed engines. However a key difference exists. It is seldom possible in premixed combustion engines to attain the optimal maximum pressure due to fast chemical kinetics. Delay in fuel injection and subsequent mixing in non-premixed engines, or multistage injection, can be used to ensure that the optimal maximum pressure is achieved in the cycle prior to attaining chemical equilibrium.

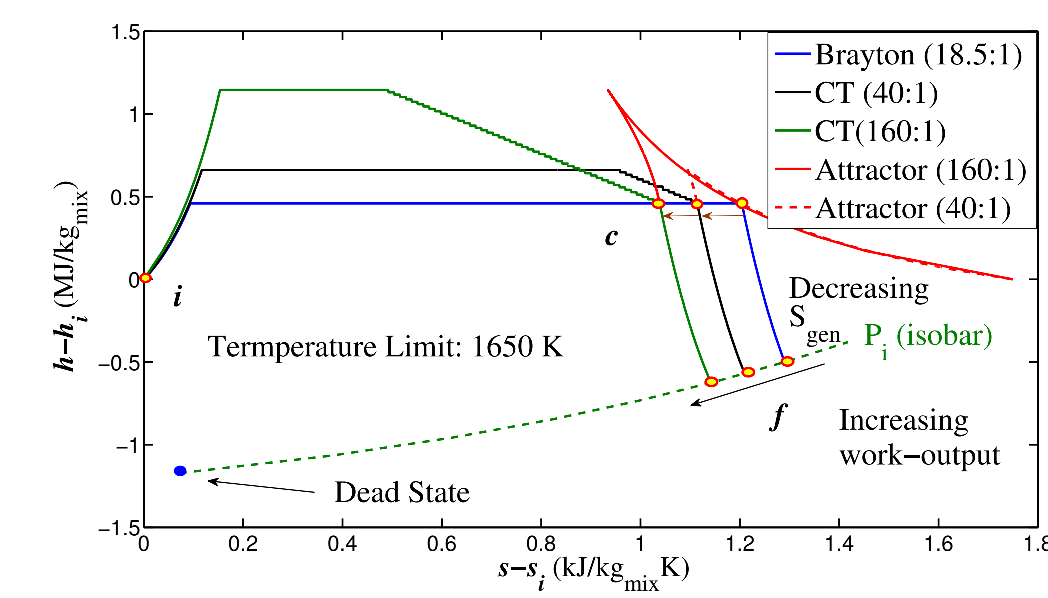
Temperature Limit

Implementation of the optimal architecture is severely restricted by the high maximum temperatures that be would encountered in doing so. The temperature constraint needs to be considered in the optimal control problem.

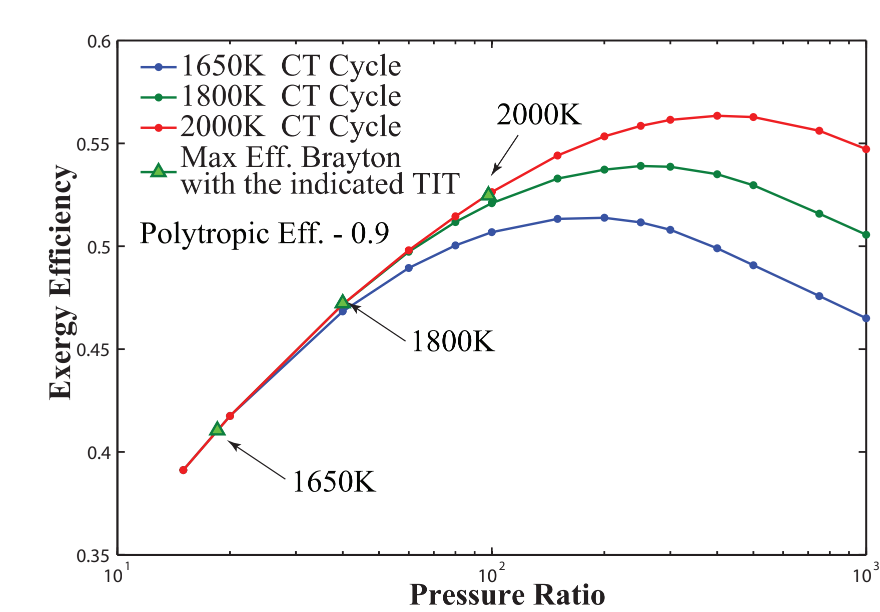
Optimal Temperature-Limited Architecture

Maximum pressure ratio in conventional steady-flow engines has been limited by the turbine inlet temperature. Blade cooling techniques and material improvements such as thermal barrier coatings have been utilized to increase the temperature limit thereby permitting higher pressure ratios. Nevertheless, the maximum pressure in existing cycles is by far significantly non-optimal. Instead of reverting back to lower pressures to meet the temperature limit we must include the temperature limit as a constraint to the irreversibility minimization problem and determine the optimal architecture again.

The solution of this constrained problem suggests a temperature-limited-combustion (CT) cycle to be the optimal architecture. The following figure illustrates two CT cycles operating at different maximum pressures and compares them with the conventional, low-pressure-ratio Brayton cycle for a maximum temperature of 1650 K.



The efficiencies that can be obtained in simple-cycle engines based on the optimal CT architecture are illustrated below for three different temperature limits. The maximum pressure Brayton cycle corresponding to each temperature limit is also indicated.



Conclusions & Future Work

The minimum-irreversibility, maximum-efficiency, simple-cycle, stationary-engine architecture is a temperature-limited combustion cycle. It has been shown to have higher efficiency than the Brayton cycle. A thermodynamic-optimal-control framework has been established that can be extended to undertake a systematic study propulsion engines and regenerative cycles.

Propulsion engines have two modes of work extraction, turbine work and propulsive work. Ongoing efforts involve the optimization of this two-mode work extraction process. Analysis of heat and matter regenerative engines is also in progress.

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