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 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 propulsor engines.

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 unburnt-reactants state to exhaust-products state. The thermodynamic state of the system is defined using the enthalpic representation \( u(t) = (h(t), P(t), V(t), k_e(t)) \).

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:

\[
\dot{s} = \frac{\partial u}{\partial t} \delta_{\alpha \beta} \frac{\partial \theta_{\alpha \beta}}{\partial t} T + \frac{\partial (\theta_{\alpha \beta})}{\partial t} T + \frac{\partial (\theta_{\alpha \beta})}{\partial t} M T^2
\]

\( \delta_{\alpha \beta} \) device irreversibility factors based on device polytropic efficiencies

<table>
<thead>
<tr>
<th>Control Device</th>
<th>Polytropic Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>0.65</td>
</tr>
<tr>
<td>Turbine</td>
<td>0.85</td>
</tr>
<tr>
<td>Accelerator</td>
<td>0.9</td>
</tr>
<tr>
<td>Decelerator</td>
<td>0.7</td>
</tr>
<tr>
<td>Diffuser</td>
<td>0.9</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.7</td>
</tr>
</tbody>
</table>

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:

\[
a(t) = \left( P(t), \theta_{\alpha \beta}(t), k_e(t), \dot{\theta}_{\alpha \beta}(t), \dot{k}_e(t) \right)
\]

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 can be obtained by solving the following optimal control problem:

\[
\min_{a(t) = \theta_{\alpha \beta}(t), k_e(t)} \int L(a(t), \theta_{\alpha \beta}(t), k_e(t)) dt
\]

System Dynamics:

\[
\delta_{\alpha \beta}(u(t), \theta_{\alpha \beta}(t), k_e(t)) \dot{u}(t) = \frac{\partial L}{\partial \dot{u}(t)}
\]

Reaction Kinetics:

\[
\delta_{\alpha \beta}(u(t), \theta_{\alpha \beta}(t), k_e(t)) \dot{u}(t) = \frac{\partial L}{\partial \dot{u}(t)}
\]

Optimal Pretimed Combustion Engines

The optimal control problem is solved for premixed homogeneous 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 combustor and turbine polytropic efficiencies.

Conclusions & Future Work

The minimum-inversibility, 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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