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. Research efforts on increasing engine efficiency involve parametric design, thermodynamic, and thermo-economic studies, as well as finite-time thermodynamic studies. These studies have two major drawbacks:

• A top-down approach: A thermodynamic cycle is assumed, an energy or energy analysis is performed, and its efficiency is improved by parametric optimization. This precludes other fundamentally different engine cycles that might be more efficient.
• Combustion is modeled as a heat transfer process from a heat source and combustion reversibility (that destroys about 25% of fuel energy in current engines) is assumed, thus limiting with heat transfer. This is inaccurate representation that obscures our understanding of combustion engines, and our efforts to maximize engine efficiency.

A first-principles approach is needed to obtain an optimal engine architecture from the laws of thermodynamics, that minimizes the total irreversibility and maximizes the efficiency of steady-flow engines over any other conceivable architecture subject to the same set of constraints.

Engine Architecture

An engine architecture is a thermodynamic representation of a practically implementable (real) engine. It is a sequence of permitted energy interactions, with defined interconnections using irreversible devices that are subject to practical constraints such as those arising from material strength limits. The permitted energy interactions, devices, and constraints applicable to steady-flow combustion engines considered so far are:

• Energy transfers:
  • Work – Polytropic compressors (C) and turbines (T)
  • Heat – Heat exchangers (H)
• Energy transformation:
  • Combustion – Adiabatic burners (B)
• Implementation constraints:
  • Finite-size/stage devices.
  • Wall/Blade temperature limits
  • Heat exchanger surface temperature limits, usually lower than blade limits (heat-exchanger surfaces have active heat-flux through them, therefore they don’t have TBs).
• Material pressure limits.

Optimal Architecture

An optimal engine architecture is one that minimizes the total irreversibility caused by the engine, i.e., irreversibility inside the engine (internal) and irreversibility due to engine operation (external). Minimizing total irreversibility is equivalent to maximizing efficiency.

Approach

The optimal architecture is arrived at, by sequentially adding the permitted energy interactions and irreversibility minimization at each stage. Irreversibility is minimized by a combination of analytical, optimal-control theory, thermodynamics-based proofs for ideal/non-ideal gas mixtures, and numerical simulation.

The stages studied so far in this approach are:

1. Work regenerative engines (simple-cycle)
2. Work and heat regenerative engines
3. Work and heat regenerative engines with external heat transfer to the environment.

These three stages are shown in the figure below.

1. Optimal Work Regenerative Architecture

The optimal architecture is:

1. Compression (C) to high pressure-enthalpy states
2. Combustion of a fraction of fuel in a burner (B) to reach the temperature limit
3. Staged combustion at constant temperature (the temperature limit) using alternate turbine and burner stages (TB) where n is the number of such stages.
4. Final expansion (T) after all the fuel has been burned in the staged combustion process.

Concisely stated the optimal architecture is CnBnTn.

The optimal architecture can be taken to much higher compression pressure ratios than a Brayton-cycle based architecture, and is significantly more efficient (see figure below for natural-gas turbine). The efficiency benefits are realizable with significantly fewer combustion stages than shown in the previous figure. The optimal pressure ratios for different temperature limits and the efficiencies achievable are shown below.

2. Optimal Work-Heat Regenerative Architecture

In the next step we consider regenerative heat transfers and find the minimum-total irreversibility (optimal architecture).

The optimal architecture is CnXnBnTnXn, where

1. Compression (C) by optimal pressure ratio PRopt (see below)
2. Regenerative heating (X) of post-compression gases from the exhaust to an optimal temperature TXopt (see below)
3. Combustion in burner (B) until blade temperature limit is reached, followed by staged combustion (TB) at constant temperature on the limit.
4. Expansion back to temperature TX = ΔTXopt in the hot-side temperature difference for the heat exchanger (SX opt).
5. Choice of the pair (TXopt, PRopt):
   - TXopt: Temperature of the pre-combustion state at which total irreversibility of the engine minimized. It is obtained by numerical optimization. If this is lower than the heat-exchanger-surface temperature limit, the limit TX is chosen.
   - PRopt: Pressure ratio such that all the work is extracted immediately before the regenerative heat exchanger (hot side entry pressure is atmospheric). The sensitivity to heat-exchanger temperature limit is shown below.

3. Optimal Regenerative Architecture with External Heat Transfer

The optimal architecture (CnXnBnTnXn) is the same as the previous case except with intercooled compression at environmental temperature. The optimal PR remains unchanged, but there is significant improvement in efficiency.

Conclusions and Future Work

This study is a systematic approach to engine efficiency maximization via irreversible minimization. Permisible energy interactions from physics and constraints from real-life implementation are considered simultaneously to evolve the most efficient engine architecture that,

• Has efficiency greater than any other conceivable architecture for the same constraints,
• Is qualitatively the same for any chemical fuel,
• And provides the set of parameters to be considered for numerical optimization to obtain quantitative results for constraints and fuels of interest.

Internal regenerative and external work and heat transfer have been considered so far in this approach. The optimal architecture has an energy efficiency greater than 70% for a natural-gas system.

This architecture-evolution approach will be extended to include regenerative and non-regenerative external energy transfer with matter. Multiple-work extraction architectures (similar to combined-cycles) will also be considered.

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