Research Trends In Combustion Engines - USA

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Assignment

- **Give an update on current research and development topics and activities within the U.S.**
  - **Big, big assignment**
  - **There is nothing that I know of in the activities taking place in the U.S. that I would classify as being unusual, or surprising**

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My Presentation

- Offer my opinions about the future trends in mobility powerplants and fuels
- Give a brief list of research activities of which I have some awareness
- Raise some questions on what is the potential, from a fundamental perspective, for future improvements in mobility efficiency

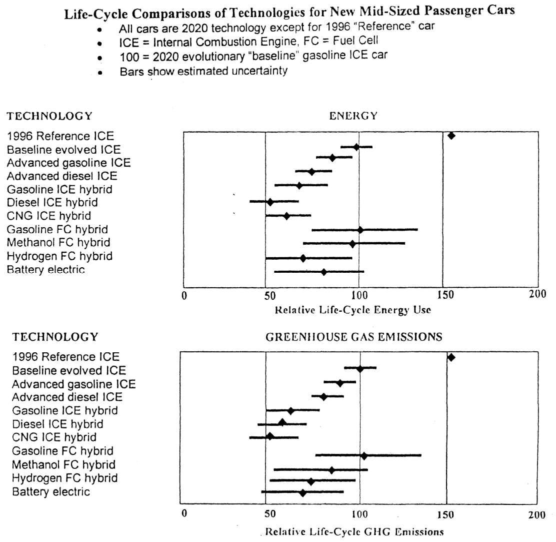
Premises for this Discussion

- We will continue to get smarter about the environmental impact of our energy conversion systems
  - continued "tightening" of "emission standards"
- Demand for personal mobility and physical transport of goods and services will continue to increase
  - maximizing efficiency is a "must"
- Petroleum based fuels will be the primary transportation fuel for the next 20 years
  - will necessarily be "cleaner" to help meet emission standards.
- Internal combustion engines will continue to be the primary energy converter for mobility for decades to come

“Wells to Wheels” Efficiency

- Both efficiency and exhaust emissions need to be considered
  - from the energy source
    - Includes process in the fuel, transporting the fuel, storage of the fuel
  - through conversion in the engine
    - Powerplant efficiency and emissions
  - to useful work done by the vehicle
    - Vehicle or drivetrain efficiency
- Processing efficiency and emissions
  - impact of manufacturing the vehicle and powerplant on natural resource use, and environmental impact

Total Energy and Carbon Emissions for Different Powerplants*



- Significant improvement over the current engines is likely
- Uncertainty is significant
- Diesel hybrid and CNG ICE hybrid seem pretty good

* On the Road in 2020, A life-cycle analysis of new automobile technologies Energy Laboratory Report # MIT EL 00-003

Internal Combustion Engines

- The are very well suited for their current application:
  - Able to meet current emission standards
  - Affordable
  - Inexpensive, high energy density fuel is currently available
    - Displacement of HC fuels with alternative energy sources from non mobile energy conversion processes would extend the "life" of HC fuels for mobility
- We need to continue to pursue improvements in fuel efficiency and reductions in environment and health impacts

Ranking of Current Powertrain Technologies

- Efficiency
  - DI Diesel > Gasoline Direct Injection > Homogeneous Spark Ignition
- Emission Technologies
  - Homogeneous Spark Ignition > Gasoline Direct Injection > DI Diesel
- Cost
  - Homogeneous Spark Ignition > Gasoline Direct Injection > DI Diesel

Increasing the Efficiency of the SI Engine

- Desire to reduce the pumping work
  - Variable compression ratio
  - Variable displacement
- HCCI, CAI, PCI etc. for selected operating regimes of the engine
- Reduce friction

Future Development of the Diesel?

- Emission reduction approaches
  - Combustion modifications
    - Issues with fuel injectors
  - HCCI part load operation
  - Fuel modifications
  - Aftertreatment technologies
    - SCR NOx reduction
    - NOx traps
    - Particulate traps

Issues

- Accurate measurement of emissions, especially particulate matter at very low concentrations, is a challenge

Activities in the U.S.
DOE- National Lab – Industry - Academia

- Exploring different combustion regimes
- New catalyst development
  - Lean NOx
  - SCR Urea
  - NOx absorbers
  - Sulfur absorbers
- Particulate traps
  - Storage mechanisms
  - Regeneration schemes
- Plasma catalysis
  - Hydrocarbon SCR with plasma reformer
- Development of measurement systems and sensors
- CLEERS (Crosscut Lean Exhaust Emission Reduction Simulation)

Critical Issues

- LNT
  - Aging and sulfur poisoning
  - NOx reduction/adsorptions kinetics
  - Desulfation chemistry
- DPF
  - Particle morphology, oxidation characteristics
  - PM spatial distribution and impact on maximum temperature
  - Ash creation, composition and transport vs. operation
  - Gas and nano-particle emission during regeneration

Critical Issues - continued

- SCR – non urea
  - Non-Pt catalyst additives
  - Non-standard HC reductants
  - NOx and reductant storage
  - Engine out speciation
  - Fuel reformer kinetics
- Urea/ammonia
  - Ammonia storage, distribution and introduction
  - Urea decomposition
  - Catalyst degradation
  - Effect of NO/NO_2 split
  - NOx reaction pathways and rates

Critical Issues - Kinetics

- Heterogeneous catalytic reactions including NOx reduction
- Global reactions based on lumped chemistry
- Single step (elementary reactions)
- Physio-chemical solid phase processes contributing to storage
- Gas phase reactions, including pre-catalyst reductant, NOx reactions

Is There Other Approaches to Further Increase the Efficiency of the Combustion Process?

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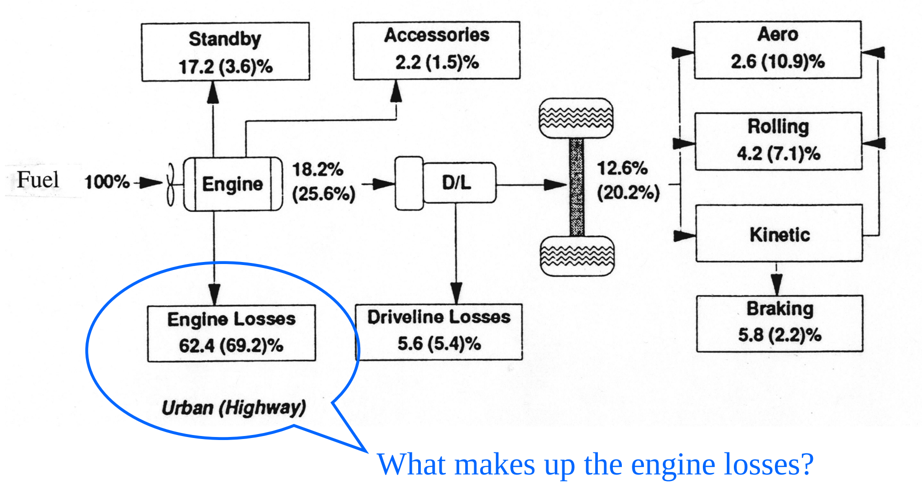
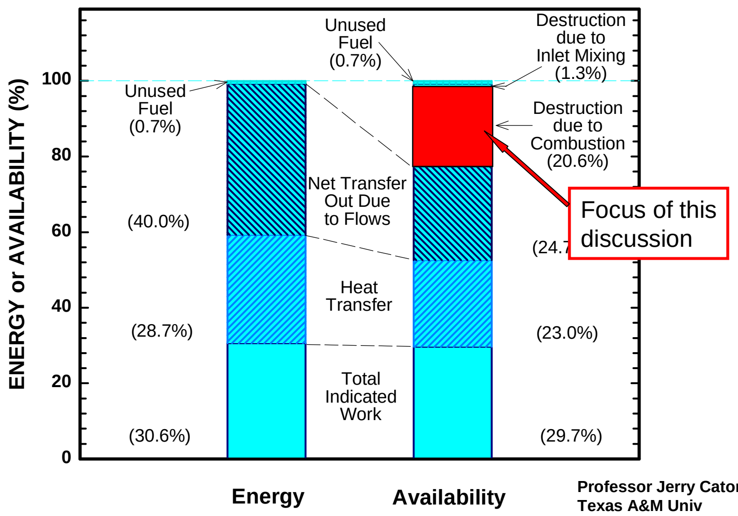
Energy Distribution in a Mid-Size Car (PNGV)



Overall Energy and Availability Values



Professor Jerry Caton
Texas A&M Univ

Classification of Combustion Irreversibilities (Dunbar and Lior)

- **Diffusion process, where the oxygen and fuel molecules are drawn together**
- **Chemical reaction**
- **Internal-thermal energy exchange, where product molecules "share" their kinetic energy with their neighbors**
- **Mixing process whereby the system constituents mix uniformly**

Losses in Combustion

$$\text{Rate of lost work } = T_0 * \dot{S}_{produced} = T_0 * \sum_{j=1}^{\tau} \sum_{i=1}^{r} \left(-\frac{\nu_i^{(j)} \mu_i}{T} \right) * \dot{\xi}_j$$

$\mu_i =$ chemical potential of i-th constituent

$\nu_i^{(j)} =$ i-th stoichiometric coefficient of the j-th reaction mechanism

$\tau =$ number of reactions, $r =$ number of species

with: $\dot{\xi}_j = k * [N_i]^{\nu_i} * [N_k]^{\nu_k}$

where: $k = B * T^n * \exp\left(\frac{-E_A}{\bar{R}T} \right)$

The Mechanisms of Loss Can Be Explained as Follows:

- The availability destruction is directly proportional to the rate at which the chemical reactions are taking place.
- The availability destruction is directly related to the affinity of the reactions that are occurring.
- The availability destruction is inversely related to the temperature at which the reactions are taking place.

Approaches to Reduce Combustion Irreversibilities

- Slowing down the chemical reactions
- Choosing fuels or establishing stoichiometries such that the chemical reactions have lower affinity
- Raising the temperature at which the reactions occur.

If It Only Were That Simple

- Raising the temperature will have offsetting effects
  - Higher temperatures will increase the rate of chemical reaction, which increases the rate of availability destruction. This will offset the reduction in availability destruction rate caused by the temperature in the denominator
- The total availability destruction will be the integration of the rate of destruction over the duration of the combustion process
  - Thermodynamics tells us that the total availability destruction will be determined by the end states of the chemical reaction process
    - Lower rates integrated for longer combustion durations will result in the same availability destruction as higher rates integrated for shorter time periods (if the end states are the same.)
- To reduce the total availability destruction during combustion, the end states need to be altered.

Question

- Is the large availability destruction currently experienced in our engine combustion processes the result of very different rates at which the chemical reaction takes place compared to the rate at which work is extracted?

Conceptual Idea and Resulting Characteristics

- Achieve energy release with “volumetric” reactions that are slow
  - Low temperature combustion
    - Low emissions of NOx and particulate matter
- More closely match the rate of energy release with the rate at which work is being extracted
  - Changing the end states

Possible Implications

- Irreversibilities of reaction may decrease at the expense of lower power
- If this occurs, the available energy would be transferred to the exhaust, instead of being destroyed.
  - Exhaust energy recovery would be critical to the success of such a process

Closing Comments

- Research and development efforts on engine development in the US is similar to those taking place in the rest of the world.
- Aggressive activities to meet emission standards with diesel engine and to improve the fuel economy of spark ignition engines are underway. I am cautiously optimistic.
- New fundamental approaches to energy release that could reduce irreversibilities raise unknown trade-off issues that could alter our thinking on energy extraction for chemical reaction.

The End

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Thank you !

Credit: Shusuke Okada