Exergy Losses in Combustion

A contribution to the discussion on

"Ideal thermodynamic efficiency limits for IC engines"

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Second law analysis

- Most of this analysis is nowadays conducted on the *system level* development.

- While useful for that purpose, this approach doesn't deliver the detailed information about the specific process phenomena, often space and time dependent, which cause the exergy changes in it; The phenomena may include
  - heat transfer,
  - mass transfer,
  - fluid mechanics,
  - solid mechanics,
  - chemical and/or nuclear reactions,

  presence of fields such as gravitational, electric and magnetic.

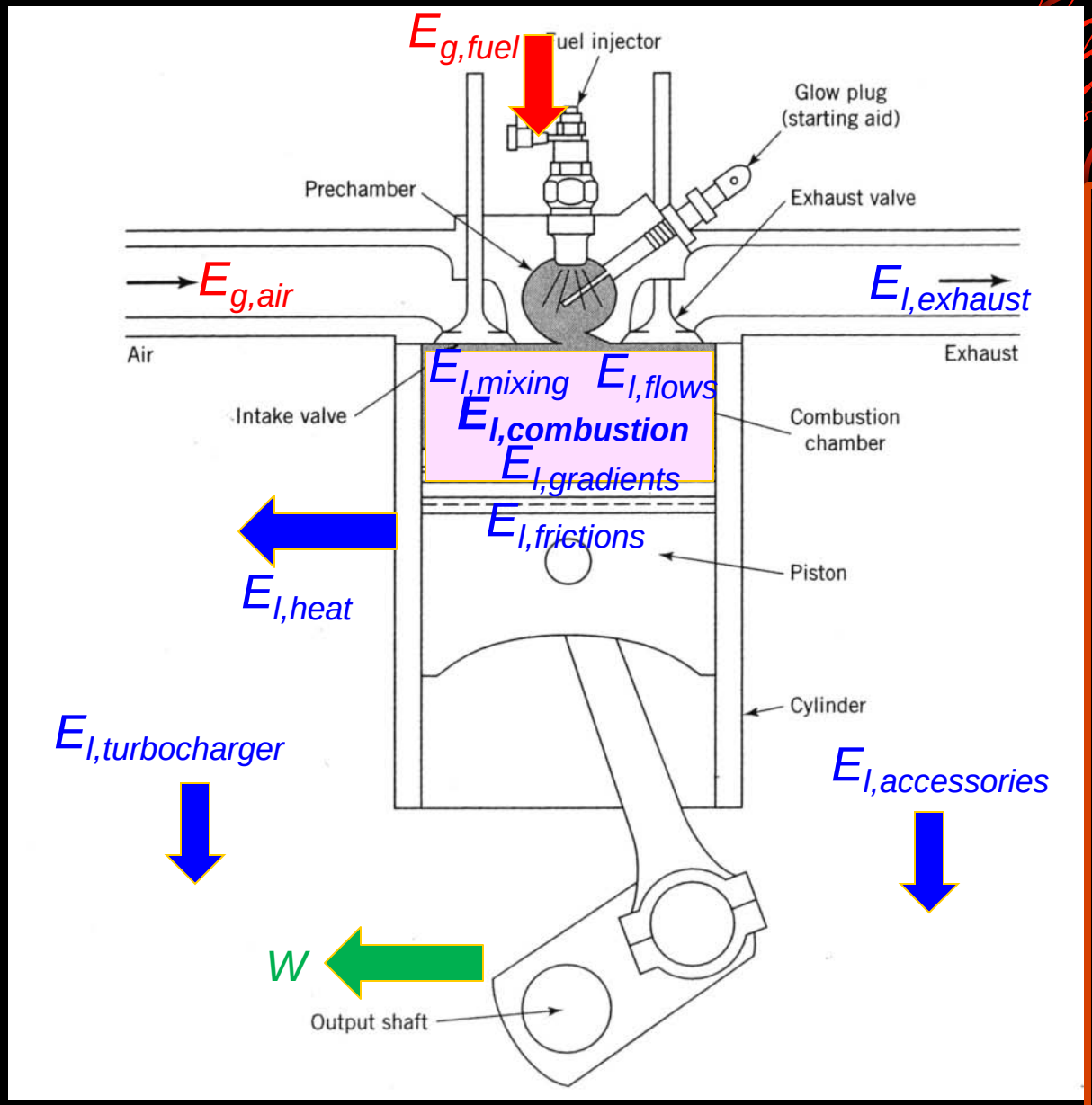
- This type of detailed analysis, which we shall call "intrinsic", is due in the second phase of system development, is invaluable in accelerating the evolution of the innovative systems needed to meet the difficult energy demands of this century.

The most important and useful objectives of exergy or entropy/exergy analysis

1. identification of the specific phenomena/processes that have relatively large exergy losses or irreversibilities,
2. understanding why these losses occur,
3. evaluation of their sensitivity to any changes in the process parameters and configuration,
4. as consequence of all these, suggestions for improvement.

All along keeping in mind the process objective!

Exergy gains (E_g), losses (E_l), and useful output ($\dot{W}$) for a Diesel engine

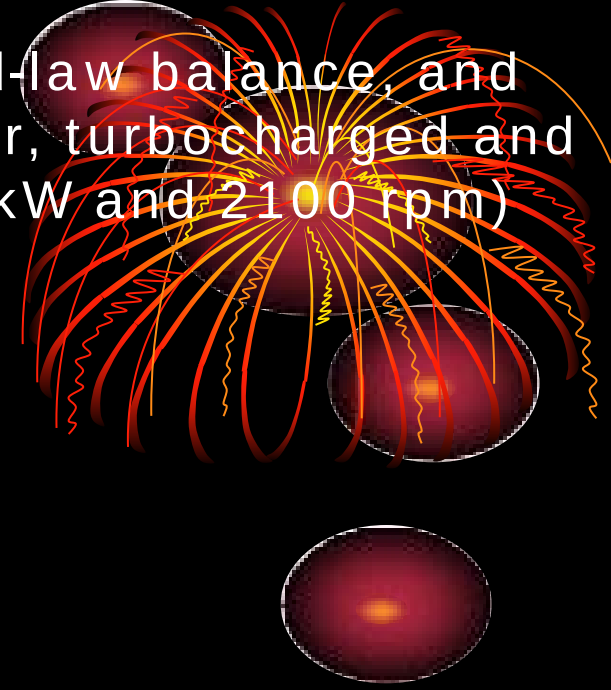


Note that the energy values are typically rather different from the exergy values of the same entities, or even absent as in the case of combustion losses, and thus do not represent well their work-loss potential and thus can not guide improvements.

Comparison of results from first- and second-law balance, and quantification of irreversibilities (six-cylinder, turbocharged and aftercooled, diesel engine operating at 224 kW and 2100 rpm)

	First-law (% of fuel energy)	Second-law (% of fuel availability)
Work	40.54	39.21
Friction	4.67	4.52
Heat transfer to the walls	17.23	13.98
Aftercooler heat transfer	5.86	1.16
Exhaust manifold heat transfer	.39	.25
Exhaust gas to ambient	31.31	12.73
Irreversibilities		
Combustion	–	21.20 (75.3)
Thermal mixing	–	0.81 (2.9)
Intake throttling	–	0.58 (2.1)
Exhaust throttling	–	1.66 (5.9)
Fluid flow	–	0.57 (2.0)
Compressor	–	1.64 (5.8)
Turbine	–	1.69 (6.0)

(numbers in parentheses denote % of total irreversibilities).



C.D. Rakopoulos , E.G. Giakoumis, Second-law analyses applied to internal combustion engines operation, Progress in Energy and Combustion Science 32 (2006) 2–47

Also: Lior and Rudy, Second-law Analysis of an Ideal Otto Cycle, ECM, Vol. 28, No.4, pp. 327-334, 1988.

Exergy-guided opportunities for engine efficiency improvements

Reduce exergy losses

- More reversible combustion
- More complete combustion at minimal excess air
- Wall and exhaust heat losses
- Reduce internal temperature, concentration ad pressure gradients
- Flow losses
- Friction
- Accessories

Partially recover exergy losses

- Add bottoming cycle(s) to use the heat losses
- Drive turbo- or super-charger
- Preheat combustion air...

All affected by compression ratio, crank angle position, injection timing, load/RPM, inlet air temperature and pressure, design of ignition zone, and other.

All are closely interconnected through reaction kinetics, fluid dynamics, heat and mass transfer, static and dynamic sructural materials behavior.

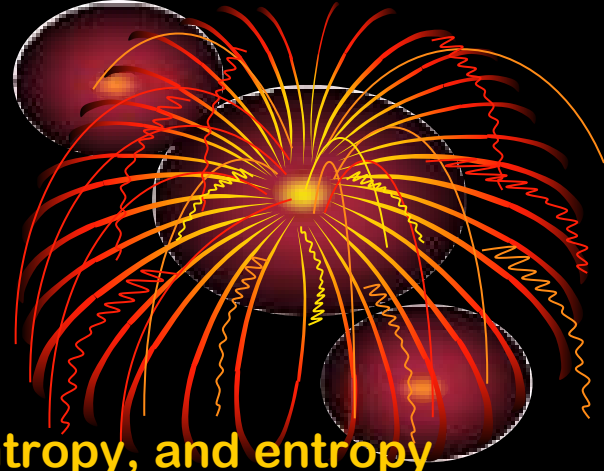
THE RIGOROUS METHOD for INTRINSIC EXERGY ANALYSIS

- Most of the exergy analysis is nowadays conducted on the system level development, by evaluating the exergy values and changes of component input and output streams and energy interactions.
- While this can indeed identify the exergy destruction in a system component, it doesn't deliver the detailed information about the specific process phenomena, often space and time dependent, which cause the exergy changes. This type of detailed analysis, due in the second phase of system development, is invaluable in accelerating the evolution of innovative combustion systems needed to reduce fuel consumption and emissions..

The exergy/entropy production field equations

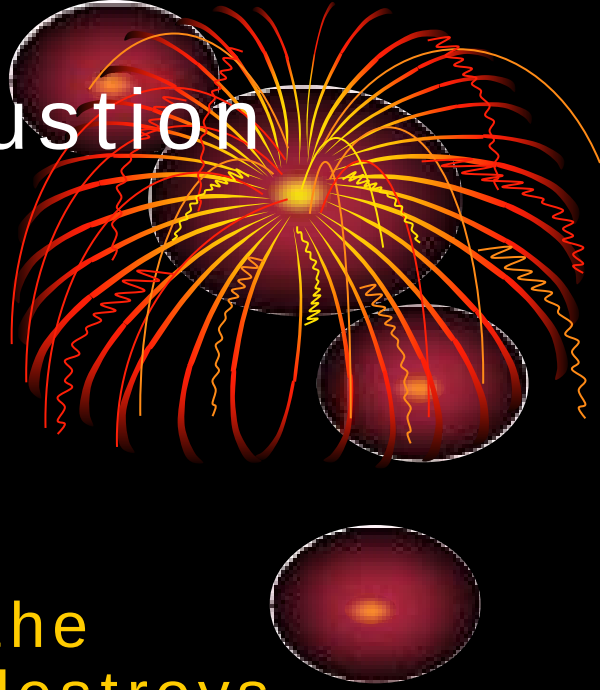
- The general transient partial differential equations for computing the intrinsic irreversibilities and exergy destruction in general are in Dunbar, Lior, and Gaggioli (1992), based on earlier work by Hirschfelder et. al (1954), Obert (1948), and Gaggioli (1961, 1962).
- Knowledge of the velocity, pressure, temperature, concentration, electrical, magnetic... fields, of the state equations, and of the chemical reactions involved, allows the direct computation of the exergy, and entropy generation, fields.

The information needed for rigorous intrinsic exergy analysis



- **To compute the exergy, exergy destruction, entropy, and entropy generation fields from these equations, we need:**
  - **the field parameters v (and hence τ), *P* (and hence also τ_n), *T* (and hence ε and σ), Ω (and hence also j_i, μ),**
  - **the state equations for the materials used, (properties (ρ,μ, *S*)**
  - **the chemical reactions involved (to determine λ,R_i,r_i)**
- **All the field parameters are obtained from the solution of the full field and state equations: Navier-Stokes, energy, species conservation, entropy generation, and thermodynamic properties and the reaction kinetics equations, all tightly coupled.**
- ***Naturally*** ( ), ***as a first step at least an order of magnitude evaluation of the different components of exergy should be performed, to determine whether they can be ignored or need to be calculated more precisely.***

Exergy analysis in combustion



Motivation

- Past studies have shown that the combustion process typically destroys about one third of the exergy of the fuel.
- Combustion of the fuel is the single largest contributor of exergy losses in fossil fuel power production.
- It is thus of great interest to determine the magnitudes and causes of irreversibility in this process.

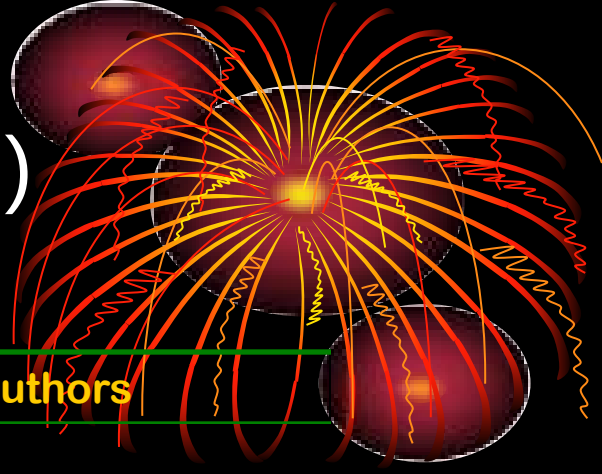
APPROXIMATE APPROACHES

- Rigorous analysis of combustion is one of the most challenging fields of science and engineering: all modes of heat transfer, set of 3-d partial integro-differential equations, many chemical reaction kinetics equations, all coupled and having a wide range of scales.
- To make the problem tractable, various simplifying assumptions are usually made, increasing the solution error.
- The rigorous intrinsic exergy or entropy analysis has indeed so far only been applied to the simplest heat/mass transfer and combustion problems, and even that required the use of a number of simplifications and empirical correlations.
- Neverthelese, simplified modeling at least partially clarifies the causes of combustion irreversibility, and some examples follow

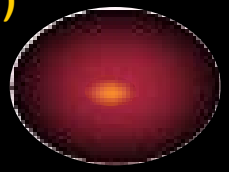
Approximate combustion/reaction irreversibility analyses

Process	Model	Conclusions	Authors
Diffusion flames	Radiative		Arpaci and Selamet (1988)
simple H_2 and CH_4 combustor	Heuristic finite increment	•The major losses are due to heat transfer •The assumed path was not so influential	Dunbar and Lior (1990, 1994)

Approximate analyses (2)



Process	Model	Conclusions	Authors
Convective droplet burning	•single control volume •empirical correlations for transport	An optimization problem between rate of evaporation and combustion (entropy increase) and resulting flow friction loss (entropy decrease due to blowing)	Puri (1992)



Approximate analyses (2)

Process	Model	Conclusions	Authors
Chemical reactions, oxidation of SO_2	•reactor in which the driving force distribution is chosen to minimize entropy production •only reaction entropy is considered	entropy production can be reduced	Kjelstrup et al., Kjelstrup and Island (1999)
IC engine static combustion	single control volume	exergy losses decrease when the temperature and equivalence ratio are increased	Caton (2000)

A heuristic finite-increment exergy analysis method
Dunbar and Lior (1990, 1994)

- The overall (global) entropy production taking place in the combustor was first modeled and quantified.
- Next, it was assumed that the combustion irreversibility is primarily caused by the subprocesses of
  - (i) reactant diffusion,
  - (ii) reaction (fuel oxidation),
  - (iii) internal thermal energy exchange (i. e., heat transfer between gas constituents within the reactor),
  - (iv) product mixing.

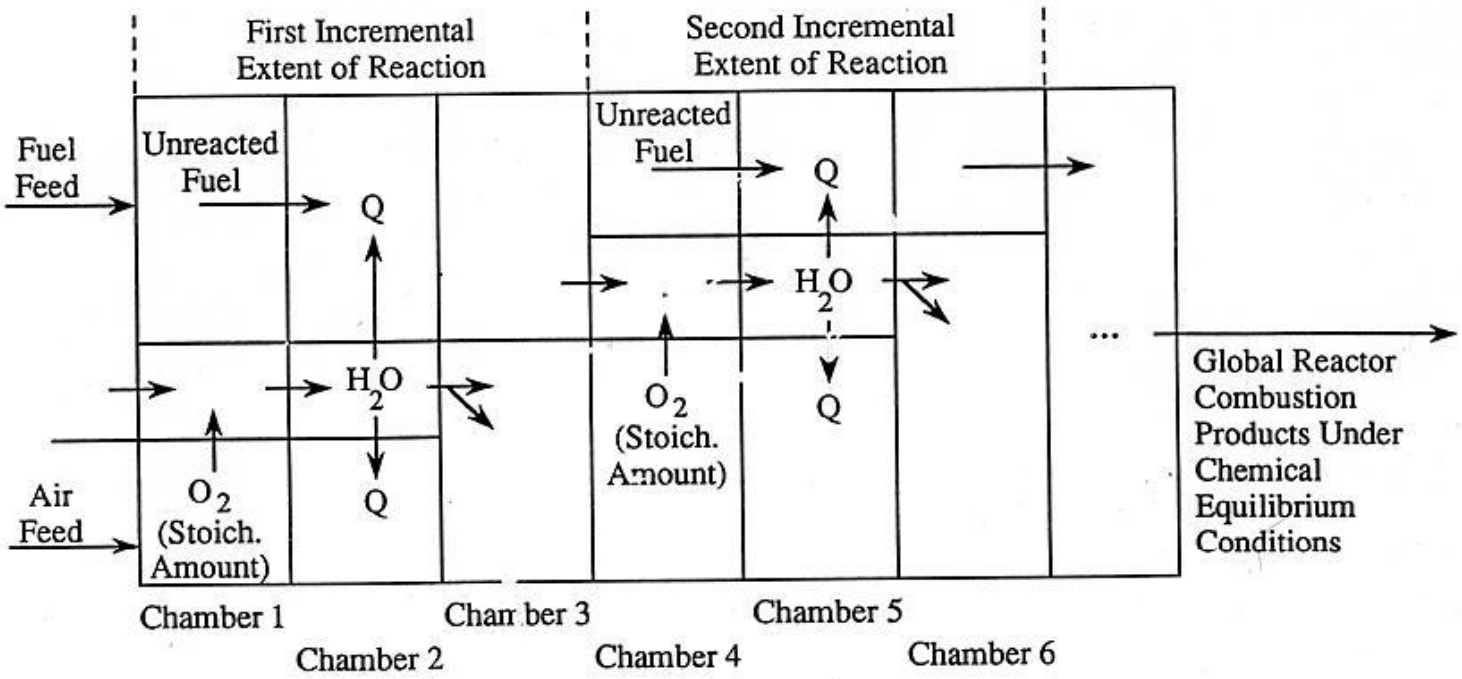
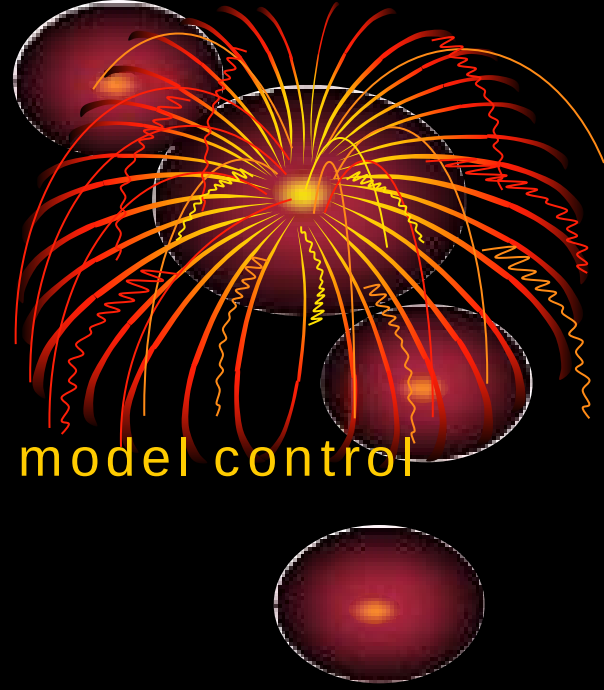


Figure 3: Hypothetical Combustion Chamber for Process Path 1

Chamber	Process
1	Diffusion/Reaction ($H_2 + 1/2O_2 \rightarrow H_2O$)
2	Internal Thermal Energy Exchange
3	Mix (Products/Depleted Air)
4	Diffusion/Reaction
5	Internal Thermal Energy Exchange
6	Mix (Products/Depleted Air)

Computation



- The entropy production rate for each model control volume can be computed by

$$\dot{S}_p = \sum_k \left(n_k s_k\right)_{\text{out}} - \sum_k \left(n_k s_k\right)_{\text{in}}$$

where the entropy of each stream *k*, s_k, can be computed from the appropriate state relations with the knowledge of the stream temperature, pressure, concentrations and any other needed parameters.

- The exergy destruction rate is calculated from

$$\dot{A}_d = T_0 \dot{S}_p$$

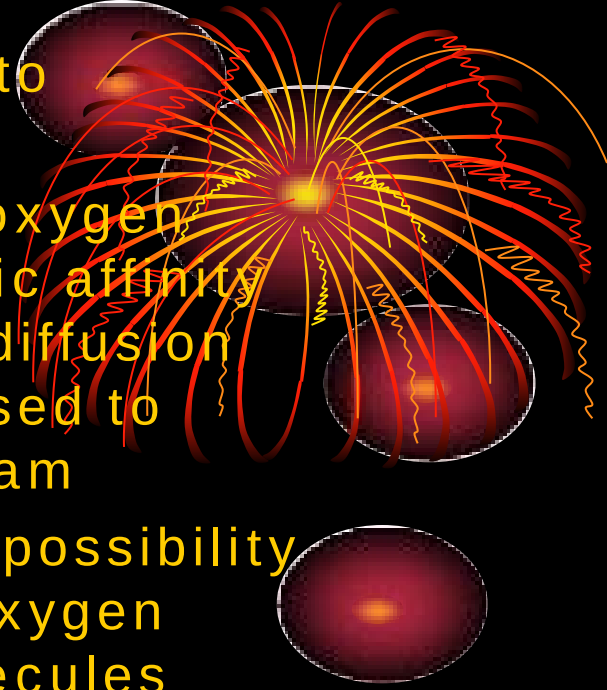
or

$$\dot{A}_d = \sum_{in} \dot{A}_k - \sum_{out} \dot{A}_k \rightarrow \dot{A}_k = \sum_k n_k a_k \rightarrow a_k = \sum_i \chi_{ki} a_{ki}$$

where

$$a_i = h_i - T_0 s_i - \mu_{0i} = h_i - T_{0i} s_i - h_{0i} - T_0 s_{0i}$$

The combustion process is envisioned here to proceed as follows:



- As the air and fuel enter the reactor, the oxygen and fuel molecules, which have an intrinsic affinity for each other, are "drawn" together in a diffusion process which consumes useful power, used to separate them from the reactant gas stream
- Having approached the fuel, and with the possibility of a number of series/parallel steps, the oxygen reacts with the fuel, forming product molecules
- During this process, there are concomitant net changes of energy in the forms of
  - (1) internal-chemical energy - energy associated with intramolecular forces
  - (2) radiation energy, and
  - (3) internal-thermomechanical energy - associated with particle motions and intermolecular forces between system constituents
- Having stabilized (reacted), these interactions between the participating species have thus added to the system entropy, destroying exergy.

Path 1 results

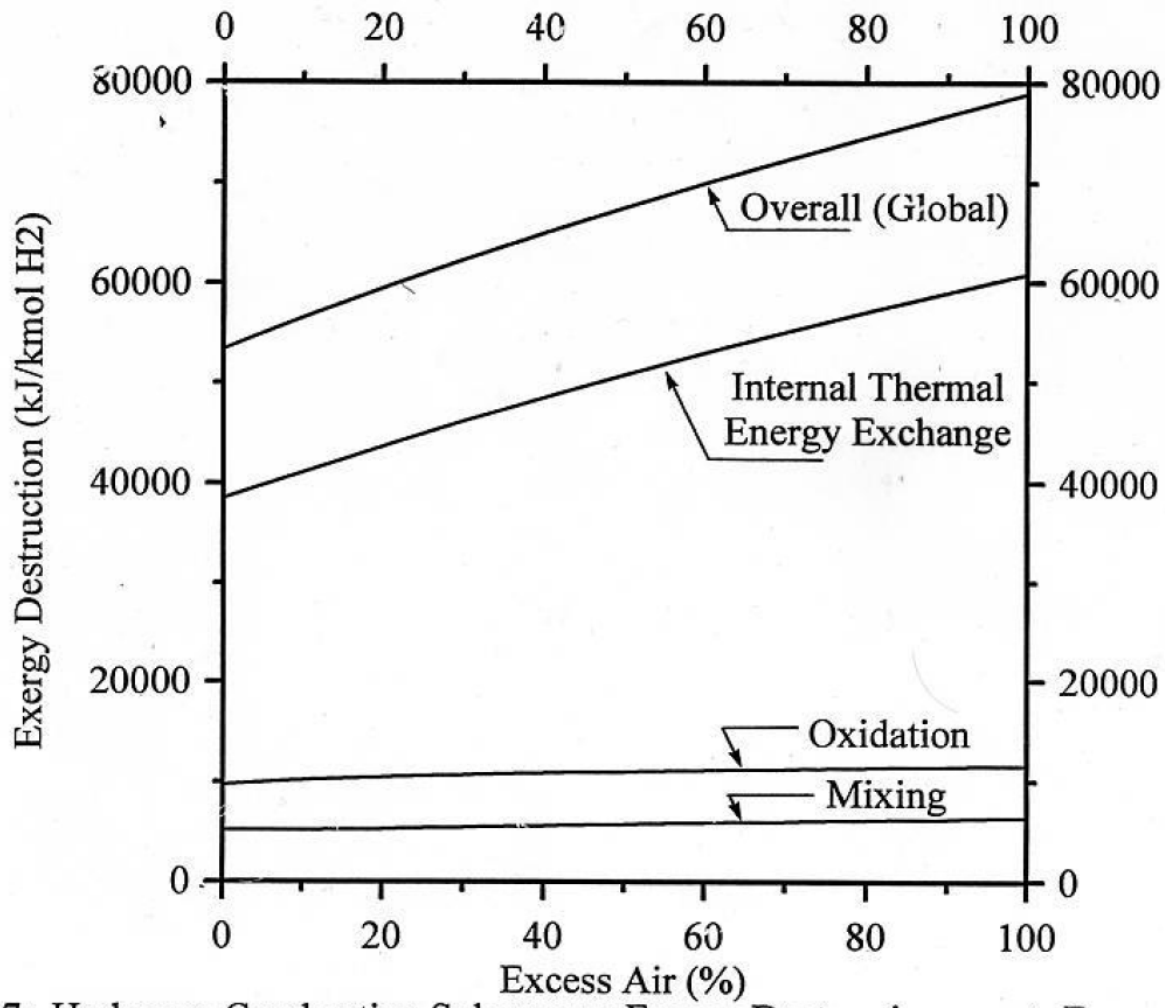


Figure 7: Hydrogen Combustion Subprocess Exergy Destruction versus Excess Air, Path 1

Path 2

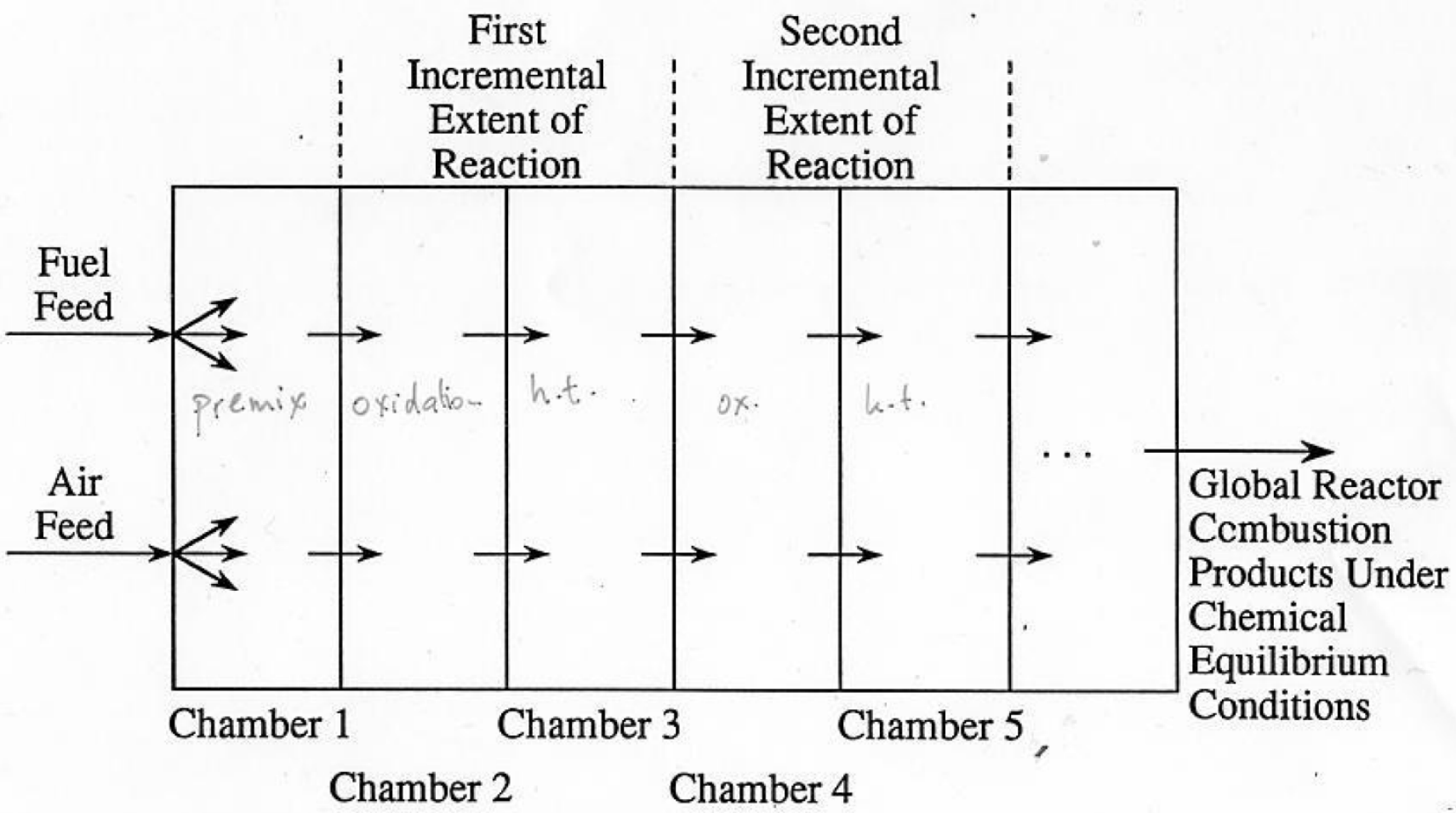


Figure 8: Hypothetical Combustion Chamber for Process Path 2

Path 3

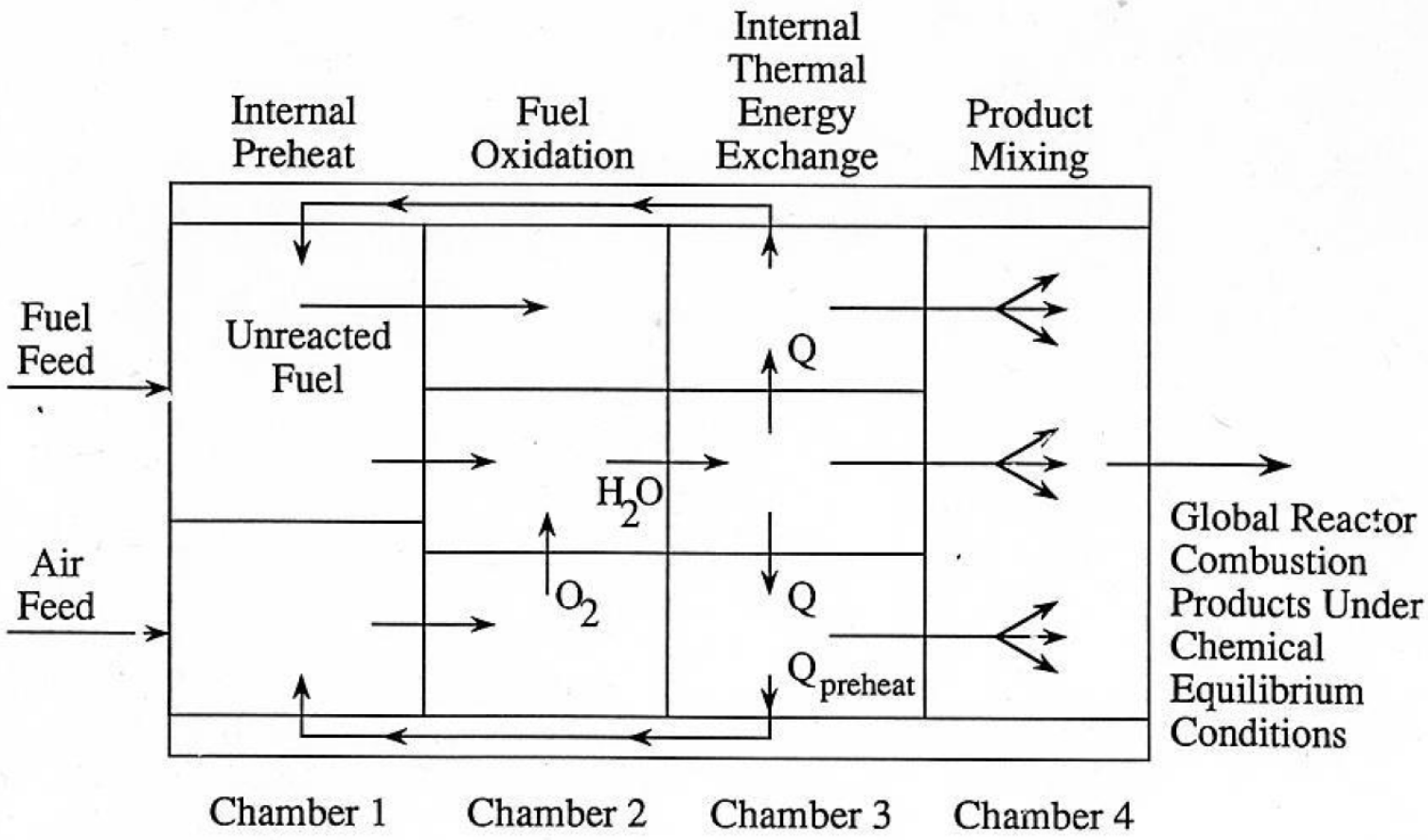


Figure 10: Hypothetical Combustion Chamber for Process Path 3

Path 4

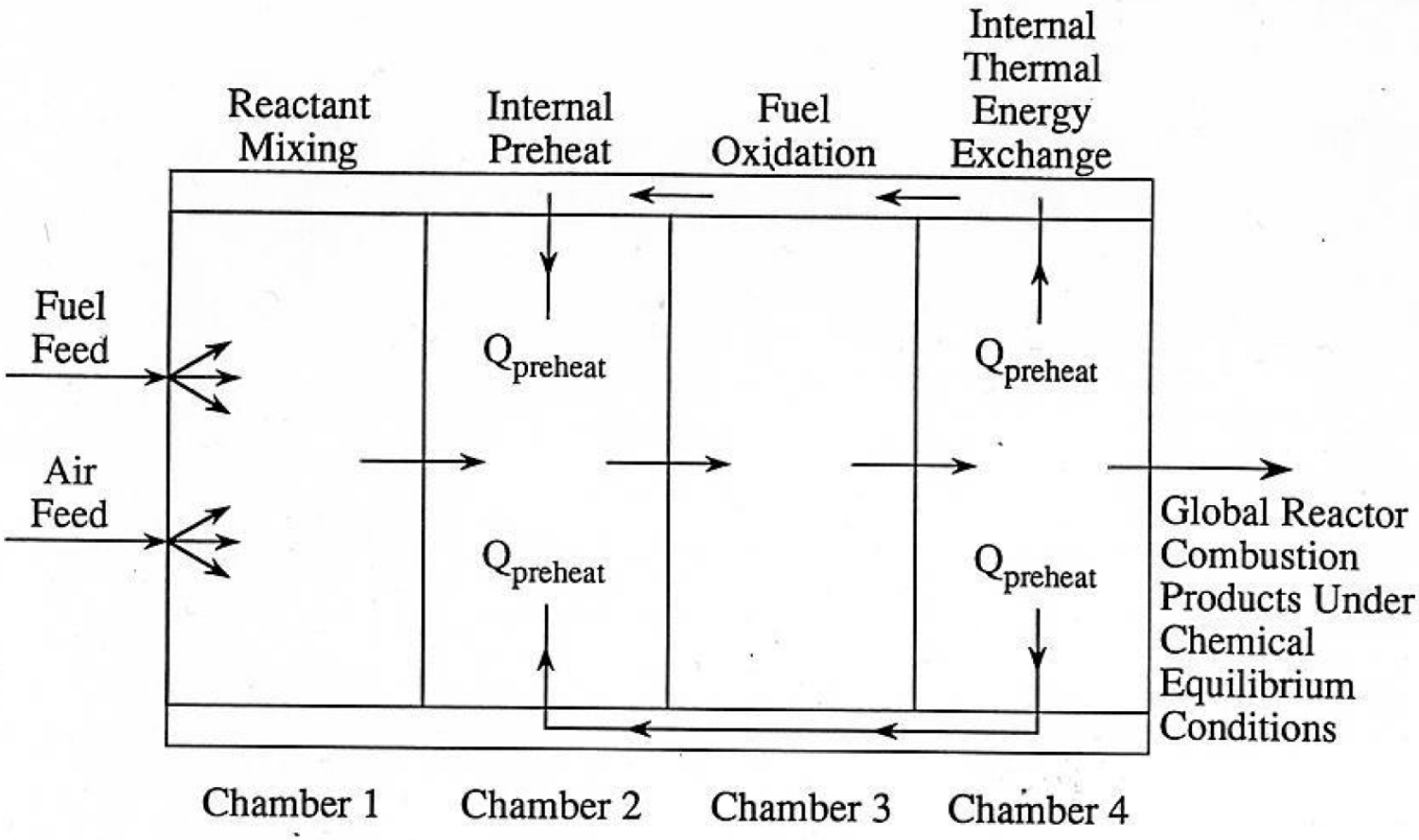
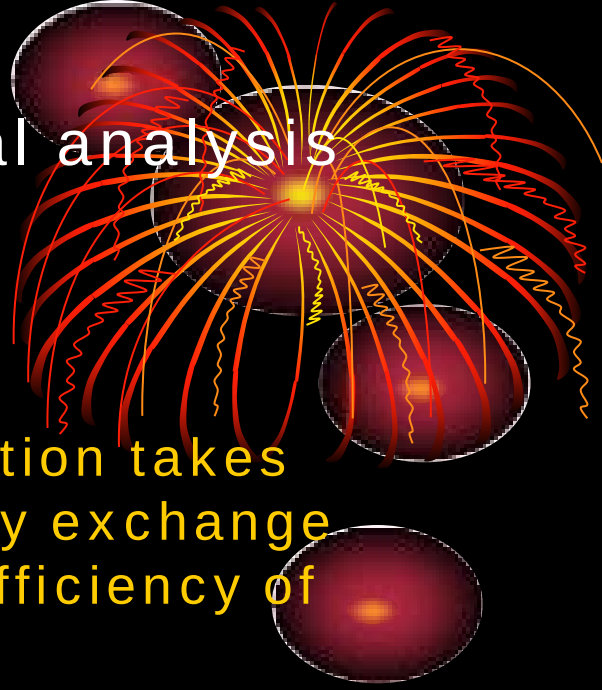


Figure 12: Hypothetical Combustion Chamber for Process Path 4

Main results from the incremental analysis



- The largest subprocess exergy destruction takes place during the internal thermal energy exchange (chambers 2, 5, etc. in Fig. 1); exergy efficiency of 73% to 83%, is:
  - decreasing with increasing amounts of excess air
  - ~72-77% of the overall exergy loss of the combustion process
- The reaction (oxidation, in chambers 1, 4, etc.) has a 94% to 95% exergy efficiency, ~15% to 18% of the total exergy loss
- gas constituent mixing (in chambers 3, 6, etc., has an exergetic efficiency of 96.5% to 97.4%, the remaining 8% to 10% of the total exergy loss.

Paths comparison

- The results for the four different hypothetical process paths analyzed show that the internal thermal energy exchange subprocess is responsible for more than 2/3 of the global exergy destruction.
- The differences between the 4 paths aren't big.

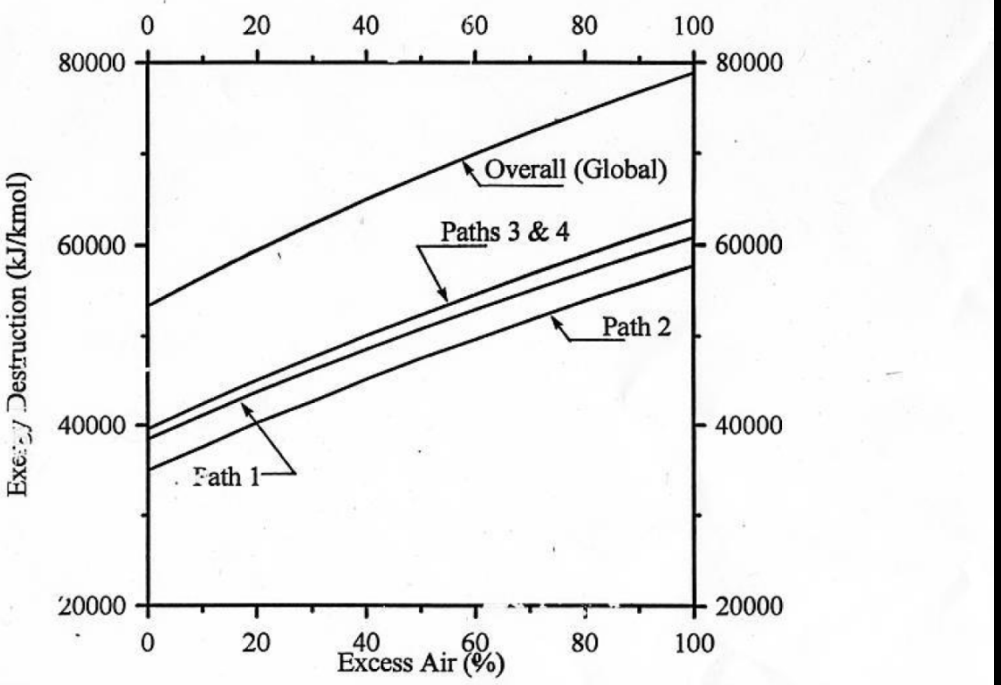
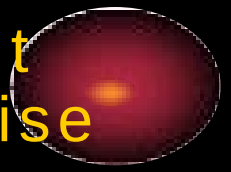


Figure 15: Exergy Destruction due to Internal Thermal Energy Exchange (for Hydrogen Combustion) versus Excess Air

An example: exergy analysis of oil droplet combustion.

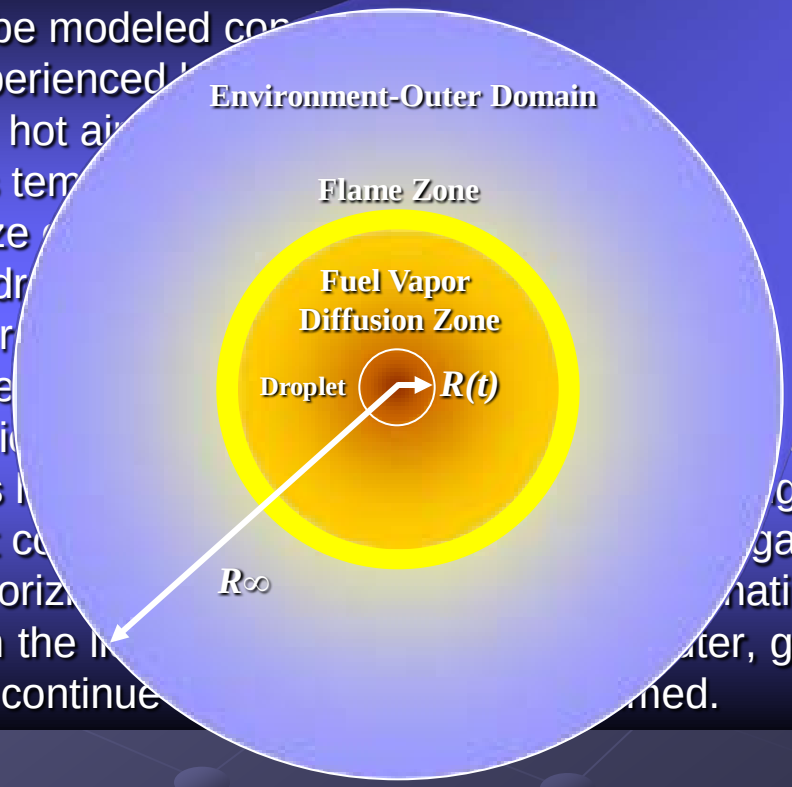


- once the droplet is introduced in the hot atmosphere, its temperature starts to rise
- consequently some of it begins to vaporize at its surface.
- fuel vapor diffuses through the hot gas until the combustion reaction starts.
- the fuel is oxidized to form carbon dioxide and water
- the combustion heat released raises the temperature of the gas and of the droplet.

Modeling and Exergy analysis of a burning fuel droplet

- **Phenomenological description**

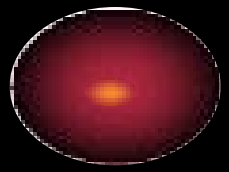
  The physical situation to be modeled co d
  pseudo steady states experienced
  introduced to a quiescent hot ai ed
  in the hot atmosphere, its tem me
  material begins to vaporize on
  rate is slow because the dr heats
  up. Fuel vapor diffuses thr
  combustion reaction is me uel is
  oxidized to form carbon di ss heat
  is released and the gas is g to the
  droplet and the other part c gases. As
  the droplet continues vaporiz nating a
  moving interface between the i ter, gaseous,
  domain. The process will continue ned.



A model was developed and solved for the transient mass, temperature and velocity fields in the gas and droplet

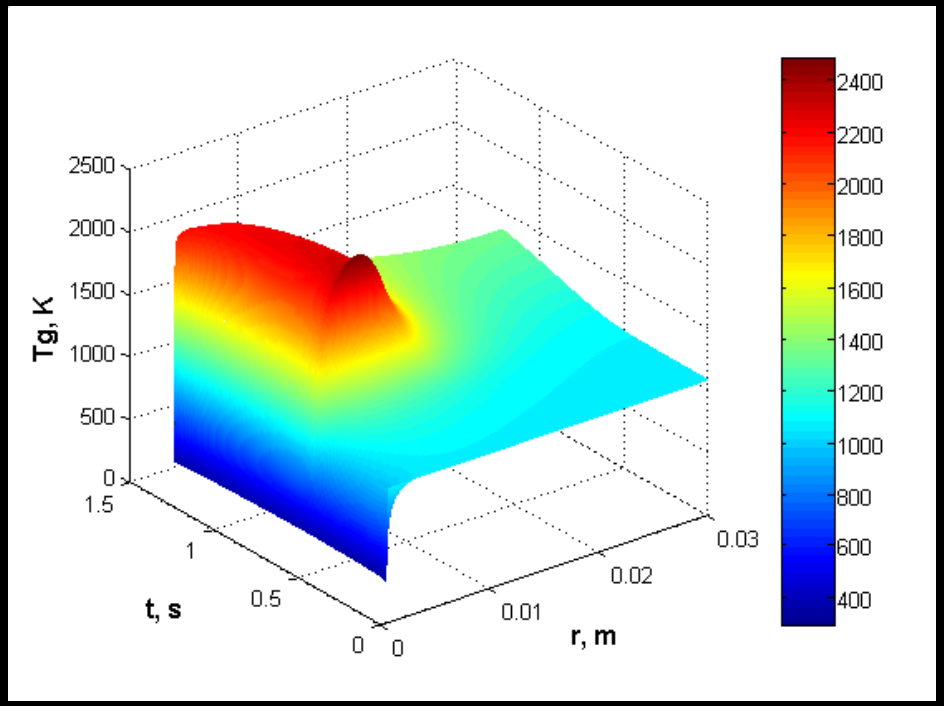
Global kinetics for the chemical reactions, assuming full completion of the reaction, the reaction rate is given by the Arrhenius form equation

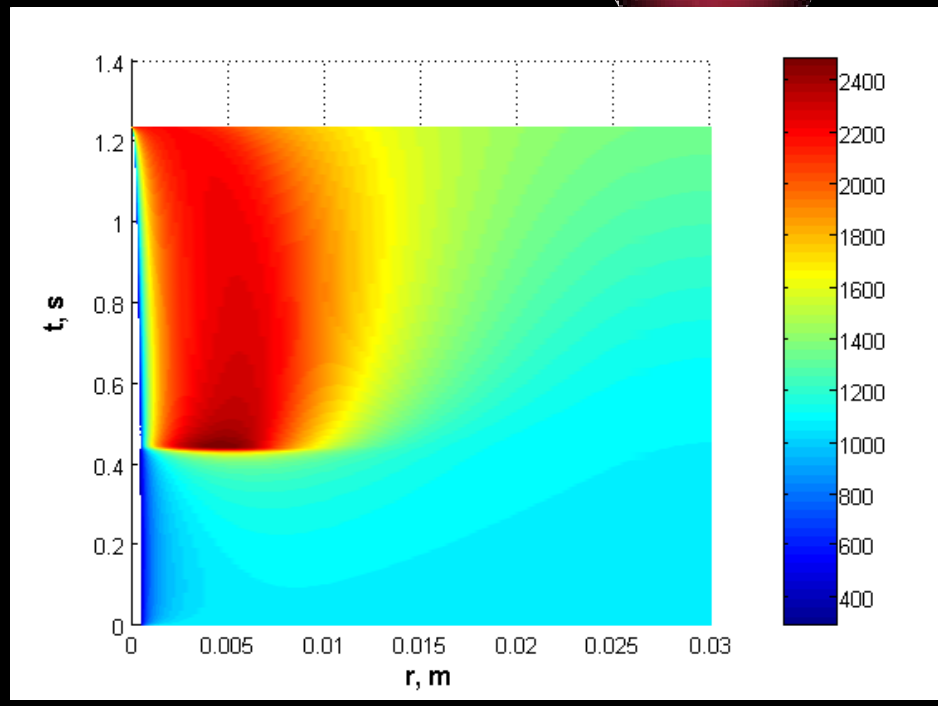
$$\dot{\omega} = A\left(\frac{\rho_g Y_F}{MW_F}\right)^a \left(\frac{\rho_g Y_{O2}}{MW_{O2}}\right)^b \exp\left[-Ae/(RT_g)\right]$$



Y_F and Y_{O2} are the mass fractions of the fuel and oxygen

The computed gas temperature as a function of distance and time for an n-heptane droplet of d_i=(1)10-4 m, T_{li}= 293 K burning in air at T_{gi}=1073 K.





Note the large temperature gradients, they cause large entropy generation

The exergy efficiency

Defining E_d as the exergy destruction in the defined control mass, and E_{in} as the exergy inflow into it, the efficiency is

$$\varepsilon = 1 - \frac{E_d}{E_{in}}$$

Compute the exergy input E_{in}

$$\dot{E}_{in} = \dot{n}_F \left[e_{F_{ch}} + e_{F_{th}} + \beta_{O_2} \left(e_{(O_2)_{ch}} + e_{(O_2)_{th}} \right) \right]$$

where n_F is the molar mass evaporation rate, and e_{Fth}, e_{Fch}, are the fuel specific chemical and thermal exergy and $e_{(O2)th}$ and $e_{(O2)ch}$ are the oxygen specific chemical and thermal exergy, respectively

The exergy destruction rate

$$\dot{E}_d = T_o \dot{S}$$

$$\dot{s}_p = \sum_{j=1}^{ng} \left[\left(\rho_g D_g \frac{\partial Y_j}{\partial r} \right) \frac{R}{Y_j} \frac{\partial Y_j}{\partial r} \right]$$

Mass diffusion, S_m

$$+ \frac{1}{T_g^{\,2}} k_g \left(\frac{\partial T_g}{\partial r} \right)^2$$

Heat transfer, S_h

$$+ \frac{1}{T_g} \sum_{j=1}^{ng} s_j \left(\rho_g D_g \frac{\partial Y_j}{\partial r} \right) \frac{\partial T_g}{\partial r} +$$

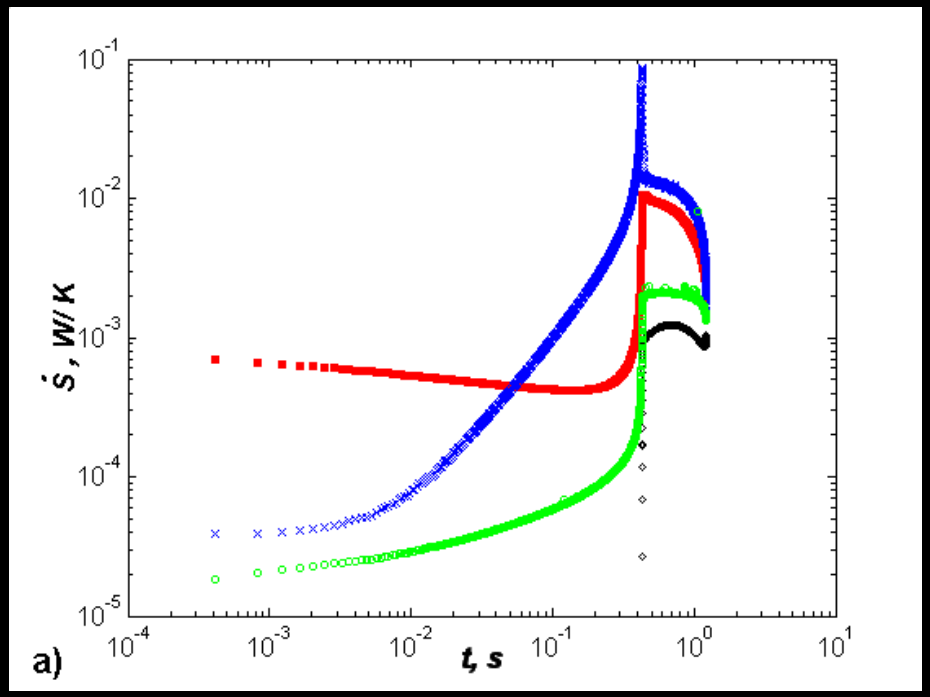
Heat&mass transfer, S_c

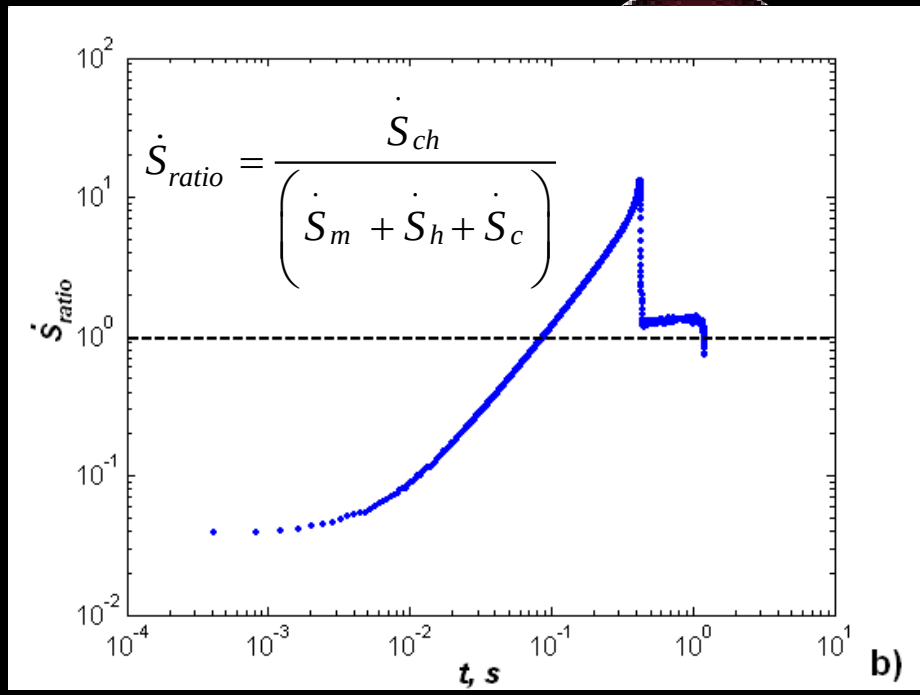
$$+ \frac{1}{T_g} \left\{ \sum_{j=1}^{ng} \left[h_j(T_g) - T_g s_j(T_g, Pv_j) \right] \omega_j \right\}$$

Chemical reaction, S_{ch}

Note: property variations may have a strong influence on *S*

Computed history of a) (x) $\dot{S}_{ch}$, (○) $\dot{S}_m$ (■) $\dot{S}_h$, and (◊) $\dot{S}_c$ and b) $\dot{S}_{ratio}$ for an n-heptane droplet of d_i=(1)10^{-4} m, T_{li}= 293 K burning in air at T_{gi}=1073 K



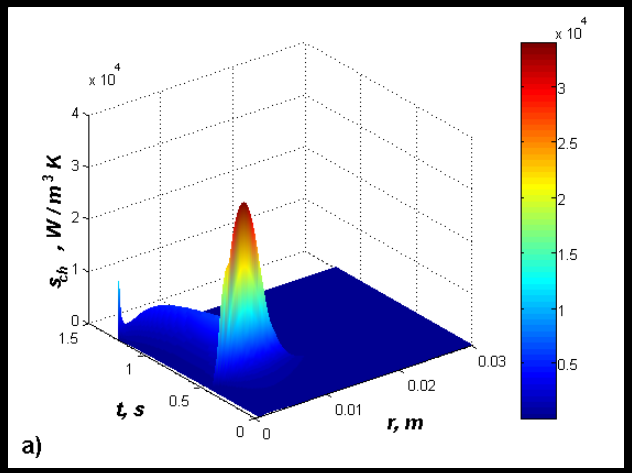


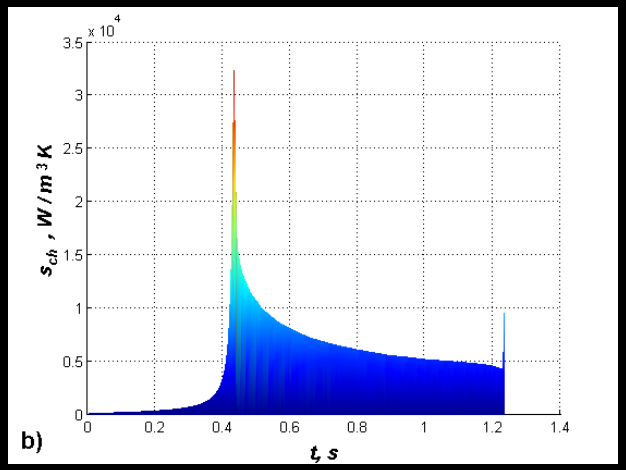
The computed a) $\dot{s}_{ch}$ as a function of position and time,

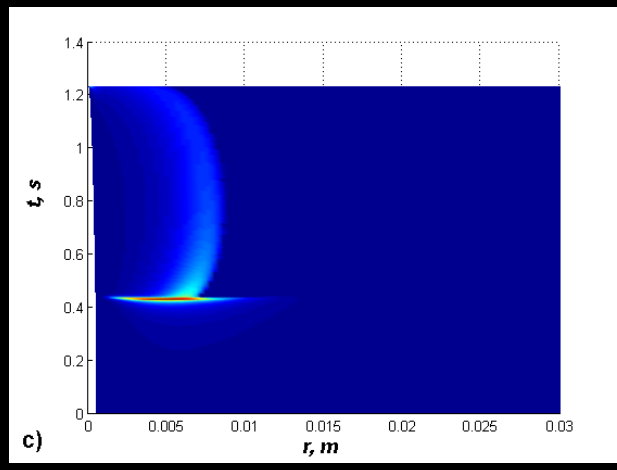
b) $\dot{s}_{ch}$ evolution in time,

c) Contour plot for $\dot{s}_{ch}$;

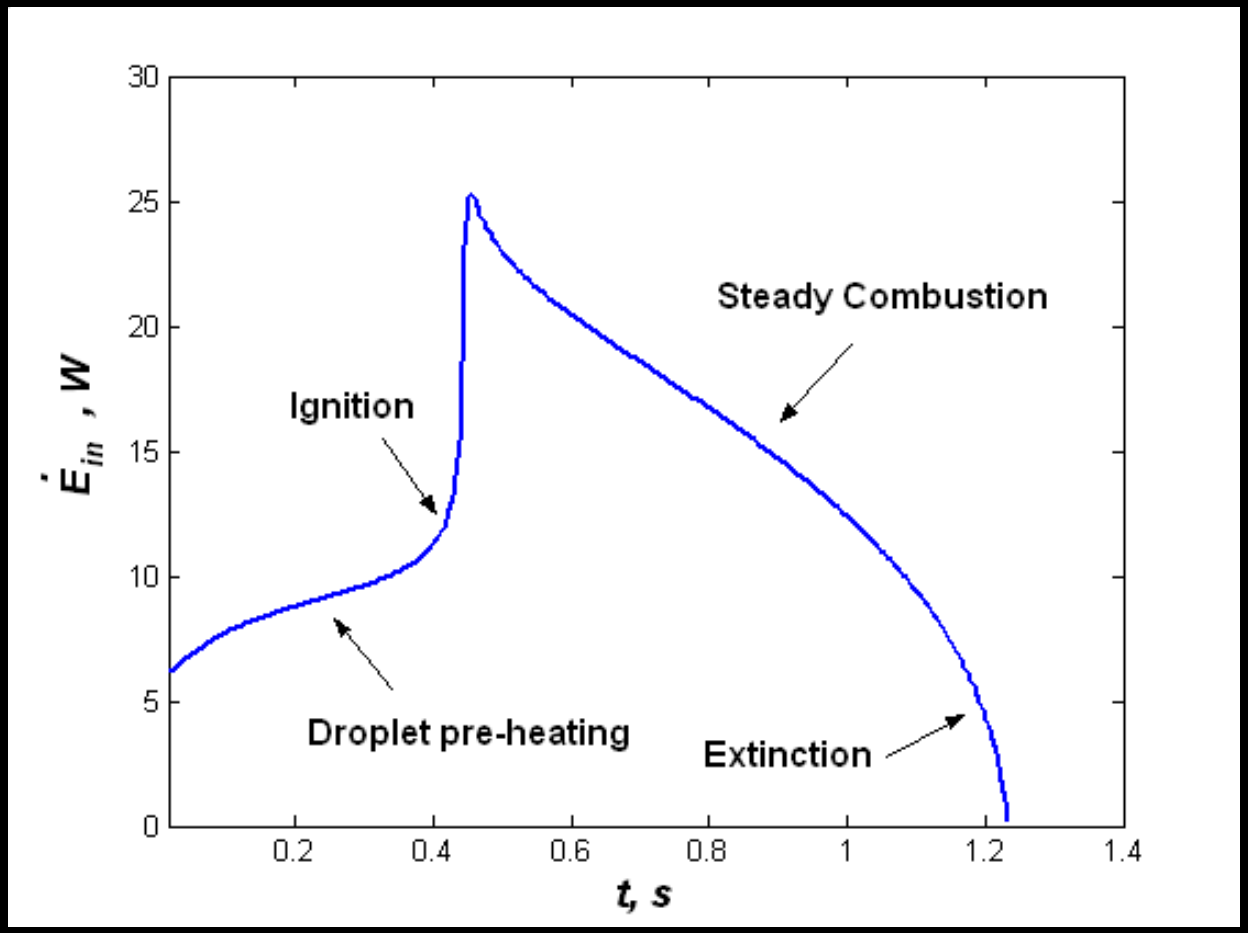
for an n-heptane droplet of d_i=(1)10^{-4} m,
T_{li}= 293 K burning in air at T_{gi}=1073 K.



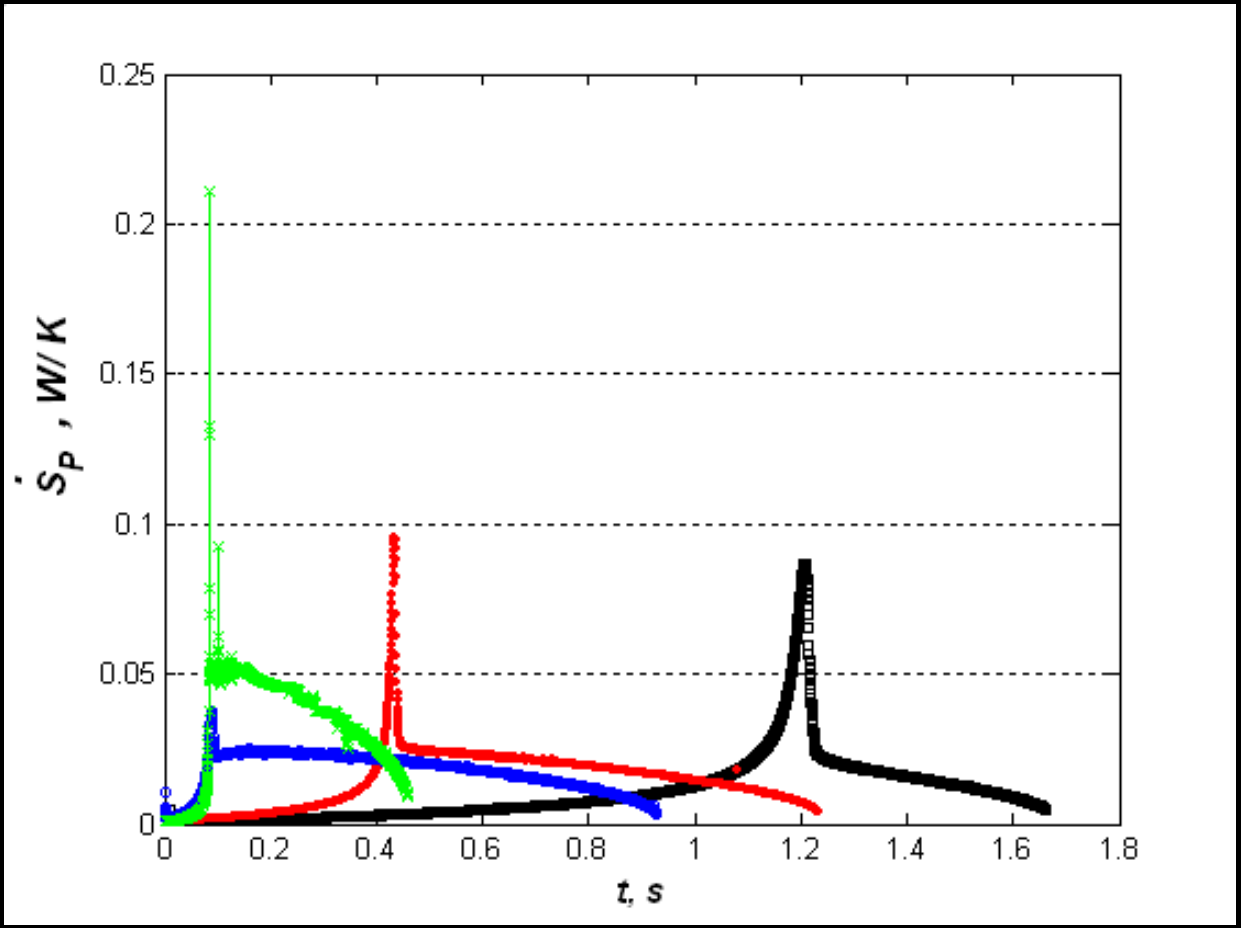




Exegy inflow ($\dot{E}_{in}$) as a function of time for an n-heptane droplet of d_i=(1)10^{-4} m, T_{li}= 293 K burning in air at T_{gi}=1073 K.



Computed $\dot{S}_P$ as a function of time for an n-heptane droplet of d_i=(1)10^{-4} m, T_{li}= 293 K burning in air at T_{gi}=1073 K (♦);
T_{gi}=1173 K (○);
1/3 of pre-exponential factor (A) in Arrhenius eq. 2.2 (□);
fast-combustion case (70% oxygen) (x)

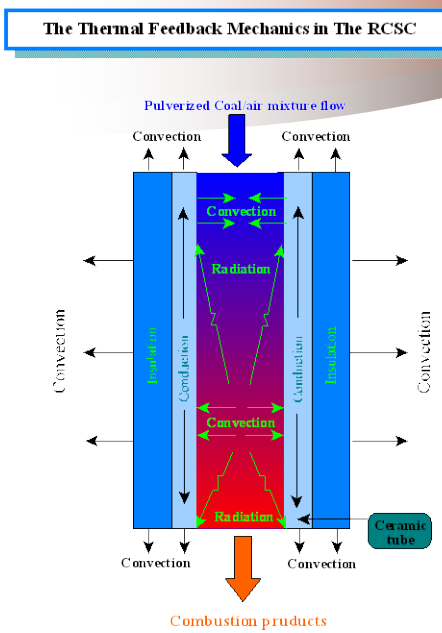


Summary of results obtained in the sensitivity analysis

Case Name	Conditions			Ignition delay time, s	Exergy destruction E_d, J	Exergy Efficiency ε, %
	T_{gi}, K	Y_{O2i} in air	Eq. (15)			
Base-Case	1073	0.23	*A*	0.432	5.140	68.4
High-Temperature	1173	0.23	*A*	0.092	4.749	70.9
Reduced $\dot{\omega}$	1073	0.23	*A/3*	1.195	5.165	68.2
Fast - Combuston	1073	0.70	*A*	0.084	4.409	73.2

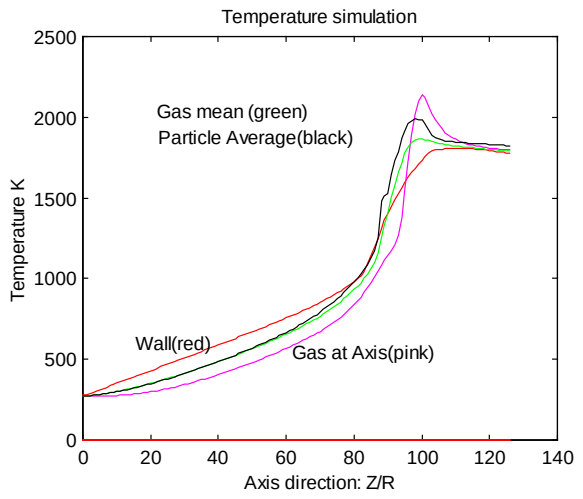
Example: Exergy analysis in a pulverized coal combustion process

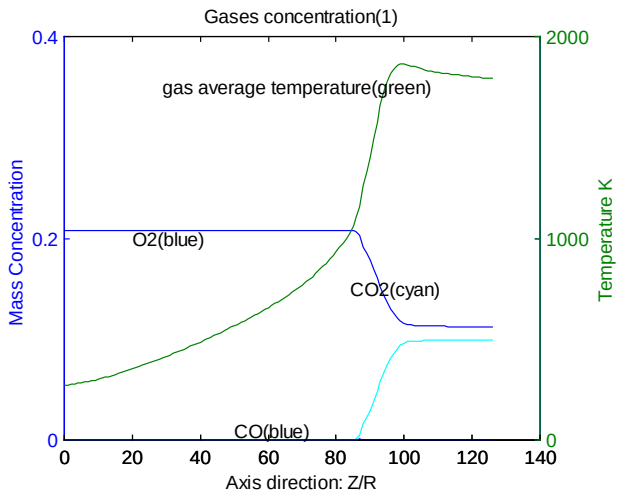
- **Based on comprehensive 3-d combustion model developed by Lior and co-workers**
- **The spatial exergy of each component and process can be computed**
- **Initial examination has shown that *K*, *Φ*, and strain exergy can be neglected**
- **Some conclusions:**
  - **The effectiveness of the exergy feedback (30% of the total)**
  - **Possibility of positioning the flame at max. exergy**

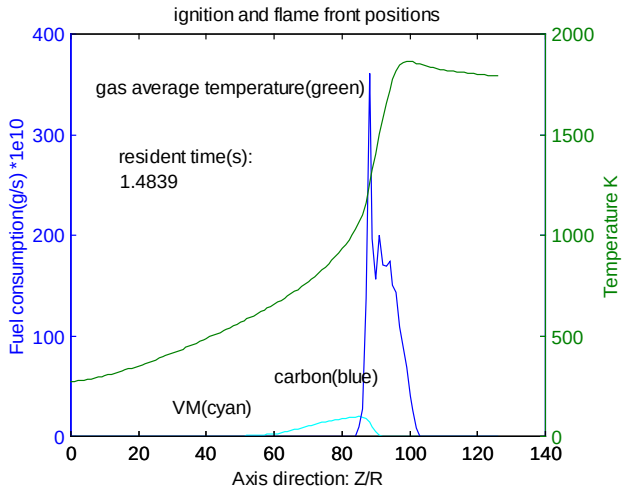


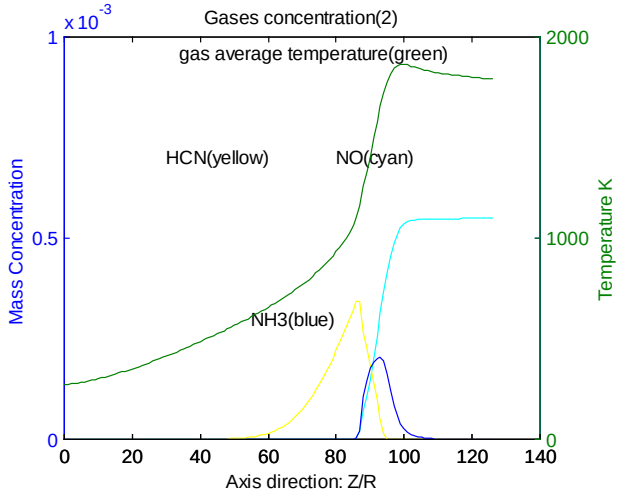
Pre-mixed coal particles and air enter the tube and are heated to the ignition temperature primarily by convection from the tube wall and the radiantly-heated particles. The hot, burned gases and particles heat the down stream wall by convection and radiation. This stabilization mode produces a very stable, oscillation-free flame. The residence time of the reactants in the flame zone is much shorter than that in recirculation burners, therefore, the RCSC yields very low levels of thermal NO_x.

Some results: concentration profiles

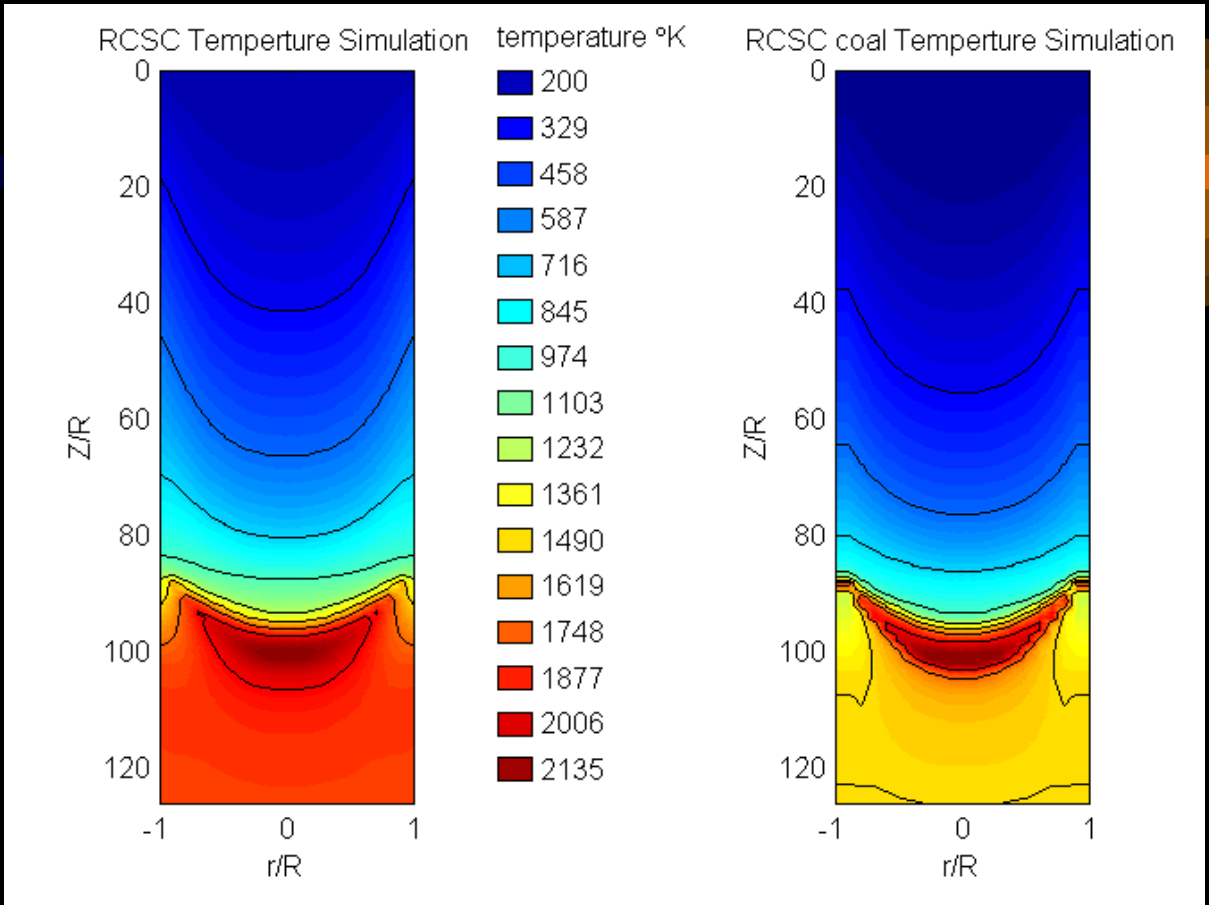






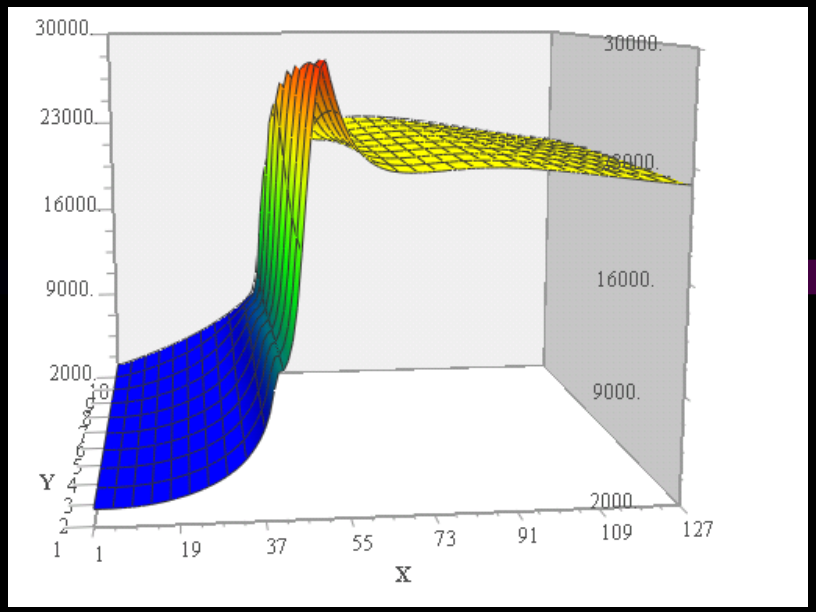


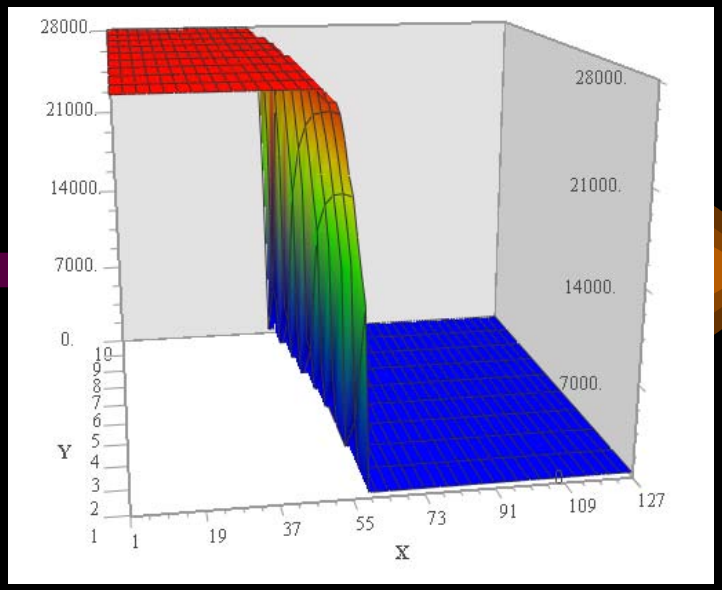
Some results: temperature fields



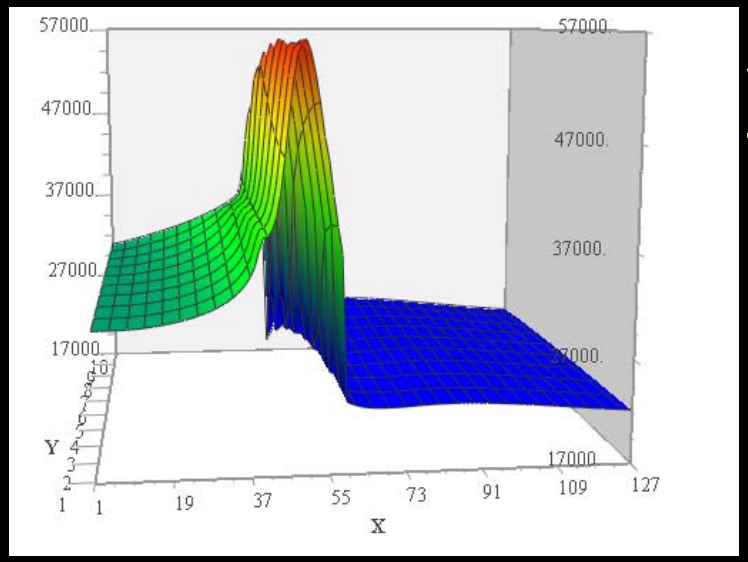
- **Gradual heating of the gas and the coal particles by convection and radiation from the combustor walls**
- **Narrow flame zone (an objective of this combustor)**
- **The radial temperature drop due to wall heat losses.**

Exergy distributions





Thermal:
follows closely the temperature field



Chemical: starts decreasing when the volatiles start burning, then decreases sharply when the char starts burning

Total: ~30% drop overall, >90% of it in the thin flame zone

Some exergy analysis conclusions for improvement in coal combustion

- In the investigated inlet temperature range of 573-973K, the exergy efficiency slightly decreased with temperature, in part because of the increased heat losses.
- The thermal feedback raises the thermal exergy upstream of the flame front to about 1/3 of its maximal value.
- An optimal combustor exit location, where the exergy is higher and yet the reactions were completed to satisfactory extent.

THOUGHTS ABOUT METHOS FOR REDUCING COMBUSTION IRREVERSIBILITY (1)

Joseph Keenan (1941) proposed the nuclei for two thermo-mechanical ideas and one electrochemical, for pursuing "reversible combustion":

• preheating the reactants to the equilibrium temperature and partial pressures without allowing reaction, followed by gradual and reversible expansion of the mixture which allows reaction to take place gradually too, and produces work till the dead state is reached. A system aimed at that process was recently proposed by Echigo (1999), where isothermality is maintained during the expansion through a turbine by having combustion proceed through the turbine stator nozzle.

•The use of, a metal oxide as an intermediate material that would combine reversibly with the fuel, and then be restored to its original condition by a reversible reaction with air. This was pursued further by Richter and Knoche (1983), Harvey and Richter (1994), Anheden and Svedberg (1998), Ishida and Jin (1994, 1996), Lyngfelt et al. (2001), Mattison et al. (2001)…

THOUGHTS ABOUT METHOS FOR REDUCING COMBUSTION IRREVERSIBILITY (2)

- Fuel cells: fuel oxidation is accomplished electrochemically, with the participation of the electrodes, and produces electricity directly rather than heat (at least in principle)

- Reaction affinity control: In a combined system, where a high temperature fuel cell is used as a topping component for gas and steam turbine power generators, Dunbar, Lior, and Gaggioli (1991) have shown that exergy destruction is reduced by decreasing the combustion reaction affinity This reduction was accomplished by using a fuel-rich mixture which is first passed through the fuel cell, where it generates power, and then the leaner mixture, now with a lower affinity, is brought to a conventional combustor for generating heat for the gas turbine.
- Or, avoid combustion in a vehicle engine altogether, use electric motor instead

Selected references to our work on combustion irreversibility (p. 1/2)

- N. Lior and G. J. Rudy, "Second Law Analysis of an Ideal Otto Cycle", Energy Conversion and Management, Vol. 28, 4, pp. 327-334, 1988.
- W. R. Dunbar and N. Lior, "Understanding combustion irreversibility", in AES-Vol. 25/HTD-Vol. 191, Second Law Analysis-Industrial and Environmental Applications, Ed. by G.M. Reistad, M. J. Moran, W. J. Wepfer and N. Lior, ASME Winter Annual Meeting, 1991, pp. 81-90;
- W. R. Dunbar, N. Lior and R. Gaggioli, "Combining fuel cells with fuel-fired power plants for improved exergy efficiency", Energy, The International Journal, Vol. 16, 10, pp. 1259-1274, 1991.
- W. R. Dunbar, N. Lior, and R. Gaggioli, "The component equations of energy and exergy", ASME J. Energy Resources Technology, Vol. 114, pp. 75-83, 1992.
- W. R. Dunbar, N. Lior and R. Gaggioli, "The effect of the fuel-cell unit size on the efficiency of a fuel-cell-topped Rankine Cycle", ASME J. Energy Resources Technology, Vol. 115, pp. 105-107, 1993.
- W. R. Dunbar and N. Lior, "Sources of combustion irreversibility", Comb. Sci. Technol., Vol. 103, pp. 41-61, 1994.

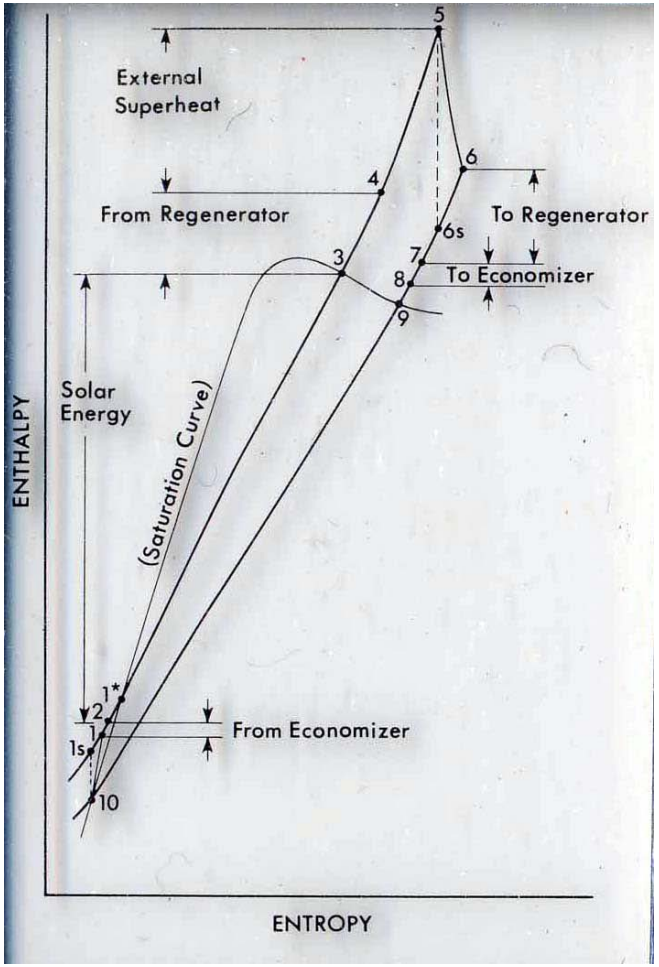
Selected references to our work on combustion irreversibility (p. 2/2)

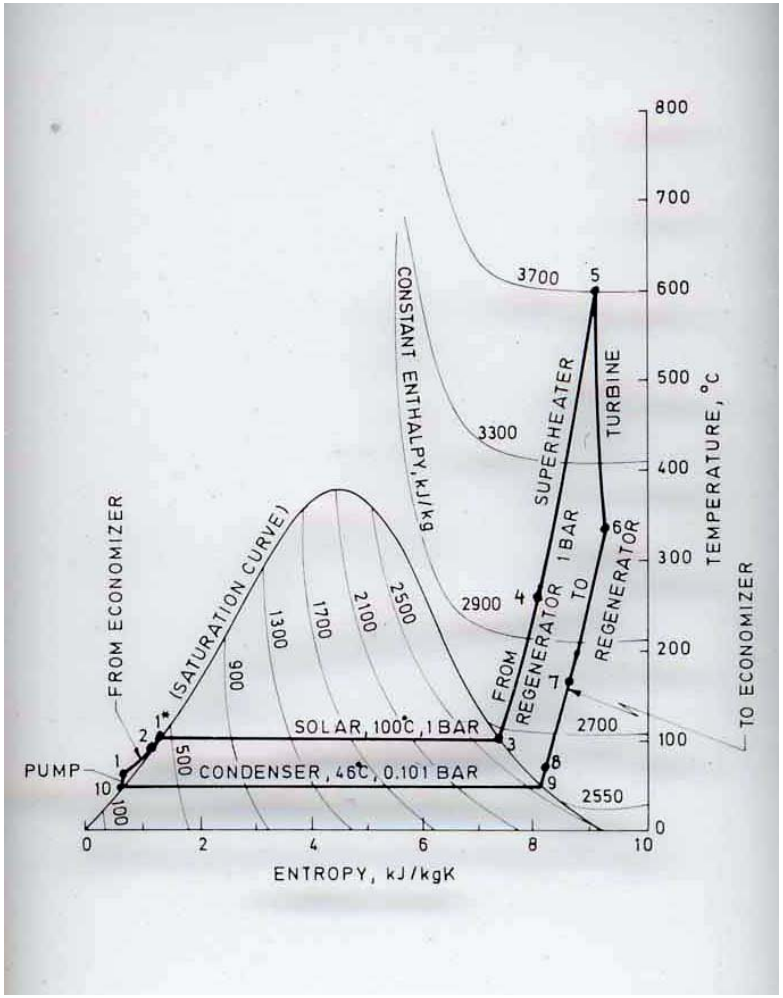
- N. Lior and S. W. Churchill, Development of a novel radiatively/conductively stabilized burner for significant reduction of NOx emissions and for advancing the modeling and understanding of pulverized coal combustion and emissions. Final Report on USDOE NETL GRANT NO. DE-FG22-97PC97273, October 2003 http://www.osti.gov/bridge/servlets/purl/821843-OcrQUQ/native/821843.PDF
- C. Kim and N. Lior, "A numerical analysis of NO_x formation and control in radiatively/conductively-stabilized pulverized coal combustors", J. Chem. Engng, Vol. 71, pp. 221-231, 1998.
- N. Lior, "Thoughts about future power generation systems and the role of exergy analysis in their development", Energy Conversion and Management J., vol. 43, 2002, pp. 1187-1198.
- I.L. Leites, D.A. Sama, N. Lior, "The theory and practice of energy saving in the chemical industry: some methods for reducing thermodynamic irreversibility in chemical technology processes", Energy, vol. 28, 1, 2003, pp. 55 – 97, with Corrigendum, Energy, 29, 2, 2004, 301-304.
- Wladimir Sarmiento-Darkin and Noam Lior, "Methodology for intrinsic exergy analysis as guide for process improvement, with a fuel droplet combustion example", ASME Paper IMECE2005-80554, Proc. IMECE2005, 2005 ASME International Mechanical Engineering Congress and Exposition, November 5-11, 2005, Orlando, Florida USA, ASME, NY.
- Noam Lior, Wladimir Sarmiento-Darkin, Hassan S. Al-Sharqawi, "The exergy fields in transport processes: Their calculation and use", Energy 31 (2006) 553–578.

Engine compounding:

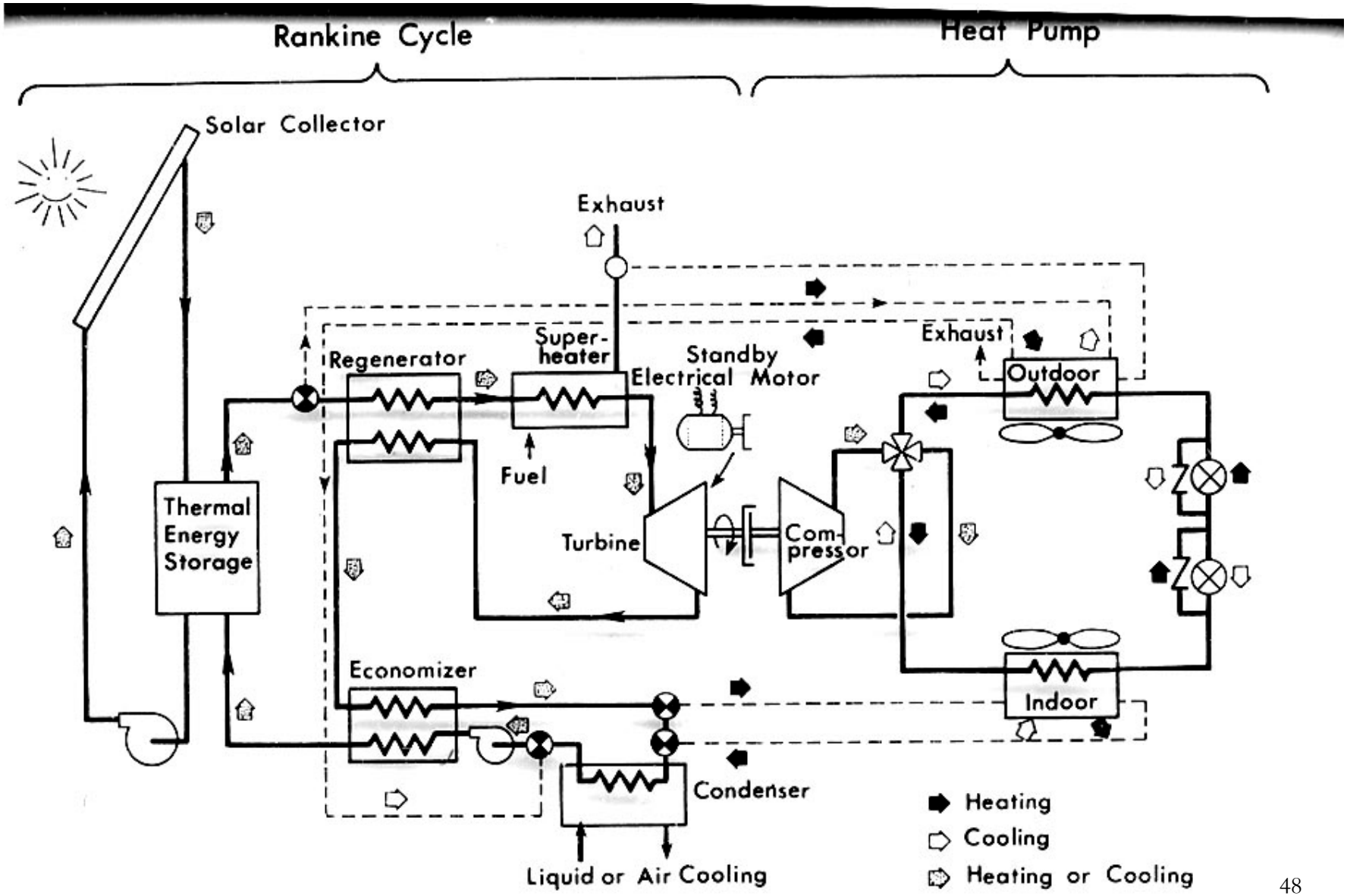
Use our hybrid solar steam powered Rankine engine (SSPRE) system concept: generate steam from radiator heat and superheat it using exhaust heat.

Our hybrid solar steam powered Rankine engine (SSPRE): thermodynamic principles

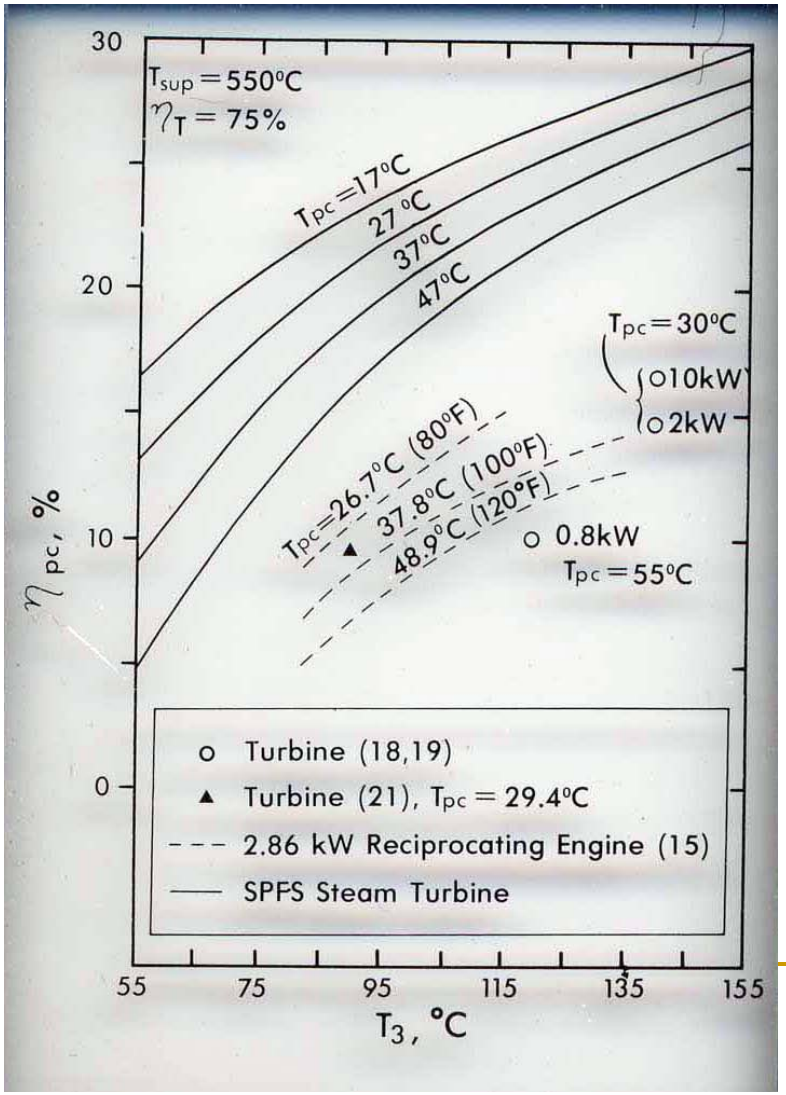


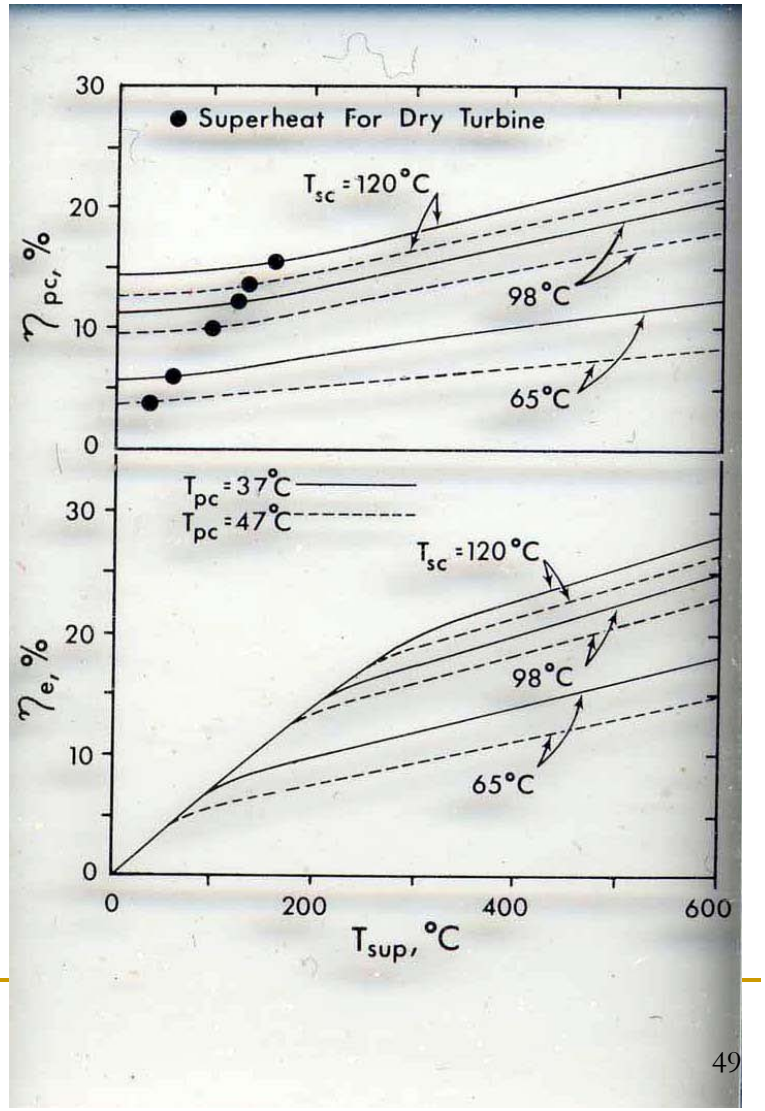


System configuration

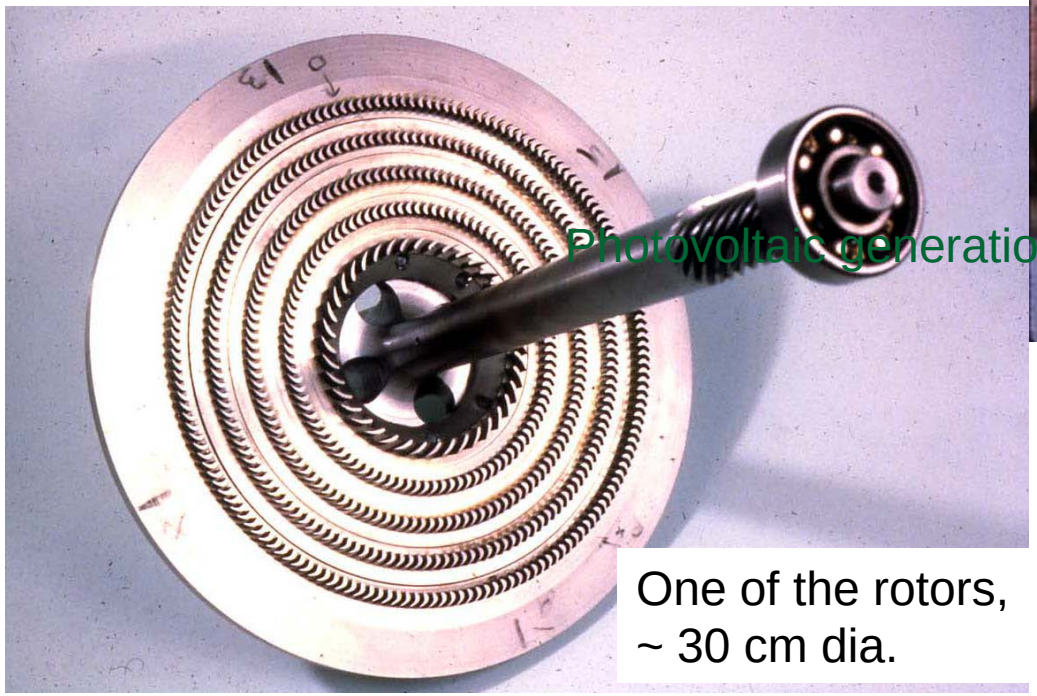


SSPRE predicted performance and major advantage: doubling the overall efficiency at the expenses of adding only 20% high temperature (such as fuel solar concentrator) heat

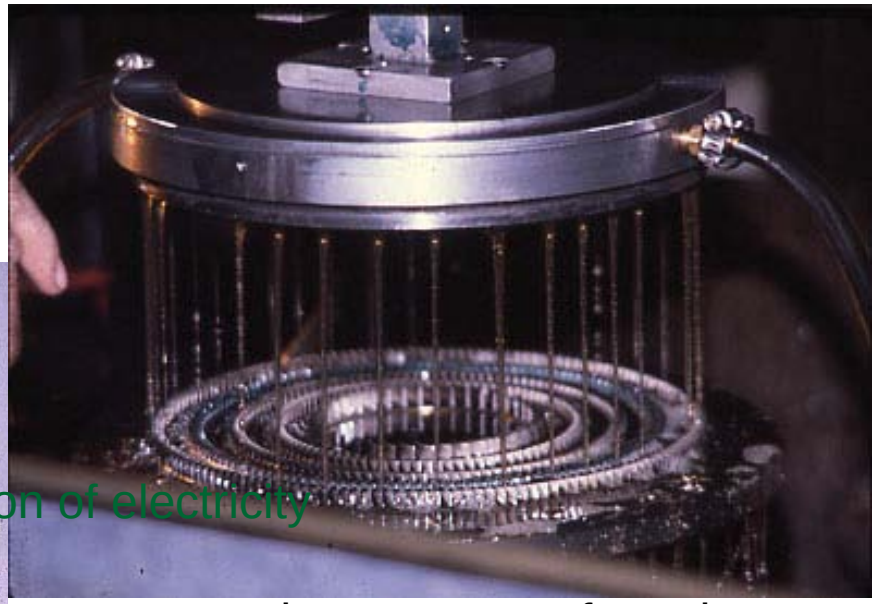




Our SSPRE counter-rotating turbine, 30hp



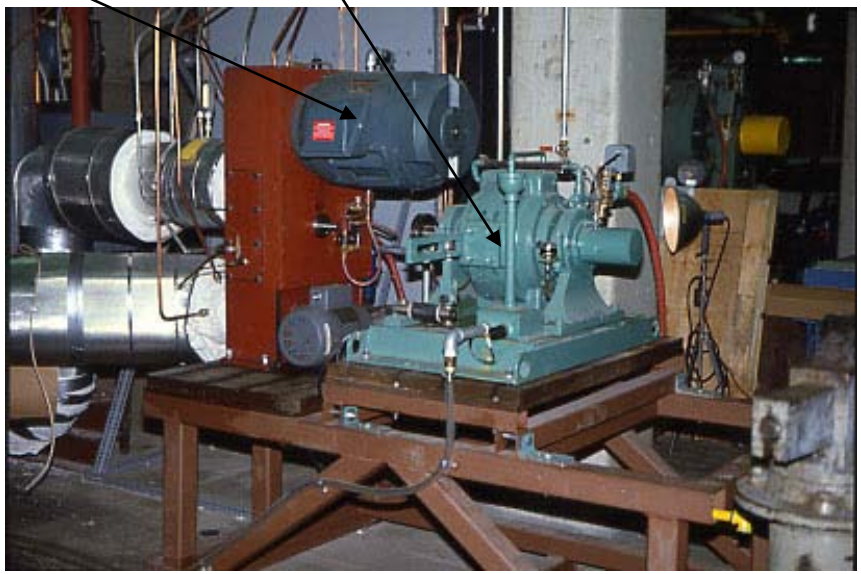
One of the rotors,
~ 30 cm dia.



The rotor manufacturing
Method: electro-discharge
machining (EDM)

Photovoltaic generation of electricity

The SSPRE turbine, gearbox, backup motor and dynamometer



Selected references for the SSPRE system

- N. Lior, N. Solar Energy and the Steam Rankine Cycle for Driving and Assisting Heat Pumps in Heating and Cooling Modes", *Energy Conversion*, 16, 3, pp. 111-123, 1977.
- N. Lior, S. Subbiah and W.J. Brady III, Jr., "Exergy Analysis of Solar Rankine Cycles Used for Cooling", Proc. ASES 1983 Annual Meeting, Progress in Solar Energy, 6, pp. 175-180, 1983.
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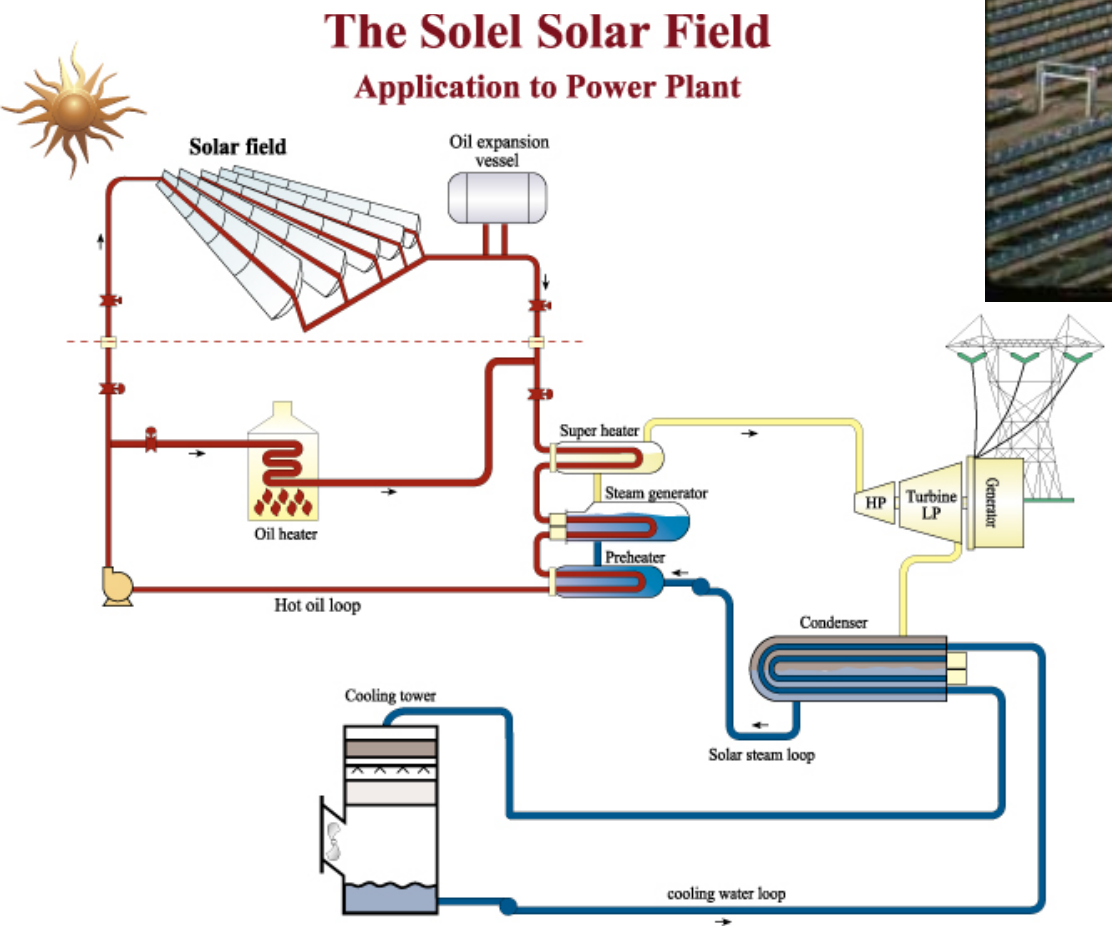
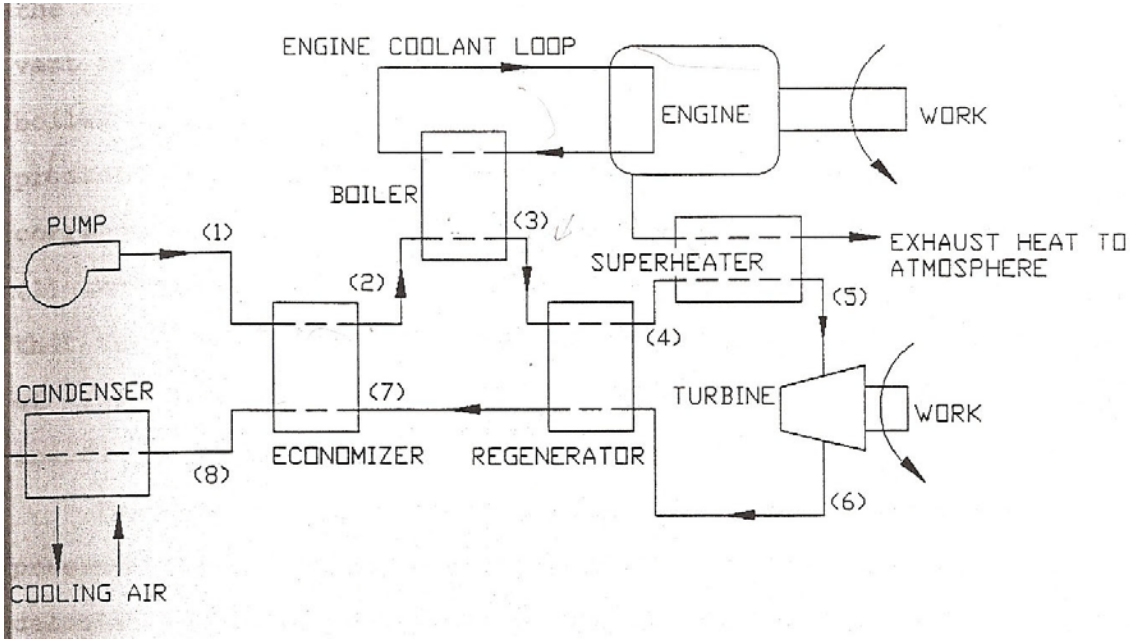
- Sherburne, D., Lior, N., 1986, Evaluation of Minimum Fuel Consumption Control Strategies in the Solar-Powered Fuel-Assisted Hybrid Rankine Cycle, Proc. ASES Ann. Meeting, pp. 300-303.
- N. Lior and K. Koai, "Solar-Powered/Fuel-Assisted Rankine Cycle Power and Cooling System: Simulation Method and Seasonal Performance," ASME J. or Solar Energy Engineering, 106, pp. 142-152, 1984.
- N. Lior and K. Koai, "Solar-Powered/Fuel-Assisted Rankine Cycle Power and Cooling System: Sensitivity Analysis", ASME J. of Solar Energy Engineering, 106, 4, pp. 447-456, 1984.

Luz solar power system, CA; 354 MW, $3000/kWe



Engine compounding: 4%-20% efficiency improvement



VERY roughly:

- Say the engine efficiency is 40% and there is 50% waste heat,
- The U of PA bottoming hybrid power cycle may reach 20% efficiency,
- Then 10% power can be generated by the bottoming system,
- Then the overall compounded engine efficiency will rise by 25%

Chemical Looping Combustion: A way to reduce combustion irreversibility

Chemical Looping Combustion; a more reversible combustion

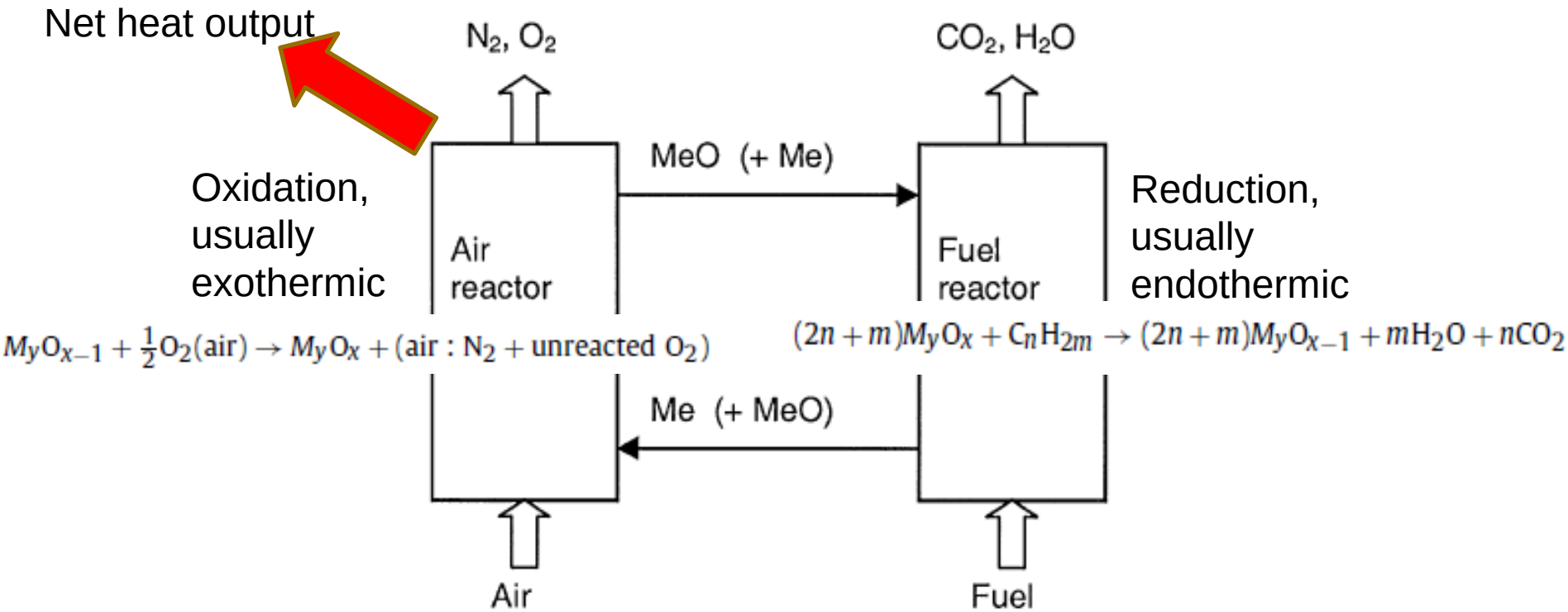


Fig. 1. Chemical-looping combustion. MeO/Me denote recirculated oxygen carrier solid material.

- Heat generation rate from fuel is the same as in regular combustion
- Needs oxygen carrier metal (Me) particles, e.g.. Fe, Ni, Co, Cu, Mn, Cd
- Their reduction and oxidation must occur at adequate rates, and they should remain active after many cycles; tested to 1200C
- At this stage not for IC engines

CONCLUSIONS AND RECOMMENDATIONS

- Creative conclusions for improving the exergetic efficiency of combustion and other chemical reaction processes can be drawn from even approximate exergy/irreversibility analysis
- The rigorous intrinsic analysis offers vastly more useful information for that purpose, and it is now increasingly feasible to compute the exergy or irreversibility distribution in combustion processes
- The method and equations for both approximate and rigorous intrinsic types of exergy/irreversibility analysis are described.
- While difficult to reduce combustion irreversibilities, it is MUCH easier by using external combustion for heat supply than by using internal combustion as done in engines
- Progress towards "reversible combustion" is slow, but very worthwhile pursuing.

Acknowledgment to coworkers and sponsors

- Basic analyses: William Dunbar, Richard Gaggioli
- Exergy analysis in the coal combustor with assistance of F. Xiong and C.S. Kim, and partially supported by a grant from the University Coal Research Program of the U.S. Department of Energy, Federal Energy Technology Center.
- Fuel drop combustion: Wladimir Sarmiento-Darkin
- Engine compounding: Michael Zdanowski, Matt Rosenfeld
- Hybrid solar steam powered Rankine engine (SSPRE): supported by the USDOE, many co-workers.