

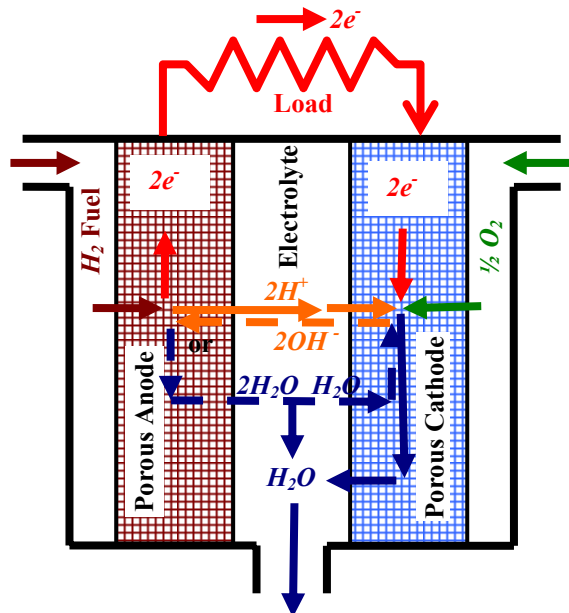
## FUEL-CELL AND HEAT-ENGINE ENERGY-CONVERSION COMPARATIVE ANALYSIS

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**Abstract** — It is well-known that fuel energy conversion to mechanical work in heat engines is limited by ideal Carnot-cycle efficiency (about 70%), due to irreversibility of combustion process alone. However, there are devices known as fuel-cells, capable of controlling electron-energy exchange more orderly, in-limit in a reversible electrochemical reaction (close to 100% efficiency), and without moving machinery and need of heating of reaction products. The practical efficiencies are usually half of their theoretical limits, about 35% and 50% for heat engines and fuel cells, respectively. Still, further developments are needed to overcome fuel-cell limitations in low power density and competitive cost.

### Introduction

A comparative energy-conversion analysis between the fuel cells and heat engines is used to unleash their potentials with regard to energy and environmental sustainability. It is well-known that fuel energy conversion to mechanical work in heat engines is



**Figure 1: Hydrogen Fuel-Cell**

**TABLE I: Energy-to-work conversion efficiencies**

Engine/Process	Efficiency %
Otto (gasoline) engine	25-35
Diesel engine	30-40
Gas turbine	30-40
Steam turbine	30-40
Nuclear, steam turbine	30-35
Combined gas/steam turbines	40-55+
Fuel cell (hydrogen, etc.)	40-60+
Photovoltaic cell	10-20
Windmill	30-40 (59% limit)
Hydro turbine	80-85
Electro-mechanical motor/generator	80-95

NOTE: Thermal-to-mechanical work conversion is limited by stoichiometric combustion temperature and the Carnot cycle efficiency. Fuel cell efficiency is limited by Gibbs free energy values for process reactants and products, and may be close to 100%. Due to material property limitations and process irreversibilities (dissipation of energy), practical efficiencies are much lower and there is room for substantial improvements. For example, existing hybrid cars have 80% improved efficiency (and mileage) over the same classical cars, from 25 to 45%, by using electro/mechanical engines/storage hybrid systems.

limited by ideal, reversible Carnot-cycle efficiency (about 70% limit), due to irreversibility of combustion process alone. The irreversibility is due to uncontrolled (rapid and chaotic) electron-energy exchange while the reactant molecules' atoms are regrouped into product molecules. The process excess-energy is spontaneously and violently (without control) released within reacting molecules, resulting in the product temperature increase. During combustion, entropy is generated and the maximum work availability (or exergy) is permanently (irreversibly) lost before the thermal energy is even used in a heat engine. However, there is a device capable of controlling electron-energy exchange by re-routing electrons from fuel molecules via external load, thus departing process excess-energy in form of work, before the reactants' atoms are isothermally regrouped into products' molecules, see Fig. 1. The electrical power is obtained in more controlled, in-limit a reversible electrochemical reaction, without need of heating of reaction products like during combustion, and without moving machinery and

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associated vibrations and noise. These devices, known as fuel-cells, work like fueled-batteries or electrolysis-in-reverse, with much higher conversion efficiencies than heat engines (close to 100% limit). The practical energy conversion efficiencies are usually half of their theoretical limits, namely about 35% and 50% for heat engines and fuel cells respectively. Efficiencies of many energy conversion processes to mechanical and electrical work are given in Table I.

In combustion, a fuel chemical energy is “released” after its molecules react with oxygen (usually from air) and transform into new product molecules. The released energy is equal to the difference in internal energy between all reacting components and all product components. If the combustion process is carried out at constant pressure or as a steady flow process, then the released energy is equal to the difference in enthalpy of reactant and product components. This energy will be spontaneously and chaotically released within reactant and product components, increasing its internal thermal energy (and thus temperature), and it may be transferred to the surroundings. Ability to extract useful work (purposeful, directional energy) from the released energy via heat transfer during combustion is limited by the ideal *Carnot* cycle efficiency, and is higher if the released energy is stored into thermal energy at the highest temperature level possible.

For a given fuel and oxidant input conditions, the maximum temperature level will be achieved if the all available chemical energy is released onto the smallest amount of combustion products and without any loss to the surroundings, i.e. if the minimum-necessary amount of oxygen (or air) is used for complete adiabatic combustion (no losses). That way maximum possible product temperature will be achieved, known as theoretical or stoichiometric adiabatic temperature,  $T_{ad}$ .

If chemical transformation of fuel molecules with oxygen is performed in “organized” way and released as work, like in fuel-cell processes, i.e. without violent release of energy into product chaotic thermal energy, then energy degradation, or loss of work potential due to entropy production (like during combustion) may be avoided. The maximum (limiting), theoretical work possible to be extracted from chemical fuel energy may be obtained in a reversible process, i.e. equal to the difference between so called maximum work availability (or exergy) between all reacting components and all product components, for the given input and output

conditions. For a special case when each and all reactant and product components are at reference surrounding temperature and atmospheric pressure, the maximum available reversible work is equal to the difference between reactants and products’ *Gibbs* free energies.

### Thermodynamic Analysis

A comparative analysis using *the First and the Second Laws of Thermodynamics* is performed for ideal combustion with ideal *Carnot* heat-engine cycle, and for ideal electro-chemical fuel-cell process, using hydrogen ( $H_2$ ) as a fuel, reacting with oxygen from air, both at reference temperature,  $T_o=298\text{ K}$  ( $25\text{ }^\circ\text{C}$ ) and atmospheric pressure ( $P_o=1\text{ atm}$ ). Similar analysis could be done for carbon or any hydrocarbon fuels ( $C_nH_m$ ). In Reference [1] (*Examples 14-10 and 14-11*) it is shown that for adiabatic combustion of methane gas ( $CH_4$ ) with 50% excess air, work lost due to irreversibility is 287,874 kJ/kmol  $CH_4$ , while the total reversible work available, but lost if the products are brought to the reference state ( $298\text{ K}$  and  $1\text{ atm}$ ) is 818,260 kJ/kmol  $CH_4$ . Since the combustion heating value is 871,406 kJ/kmol  $CH_4$ , we could easily determine the “ideal” combustion efficiency as  $1 - 287,874/871,406 = 67\%$ , and ideal fuel-cell efficiency as  $818,260/871,406 = 94\%$ . Even though ideal *Carnot* heat-engine cycle is reversible, the overall efficiency is 67% due to irreversibility of “ideal” combustion process. If theoretical air (0% excess air) were used the efficiencies would be higher since only the minimum necessary amount of the inert nitrogen would be heated during combustion.

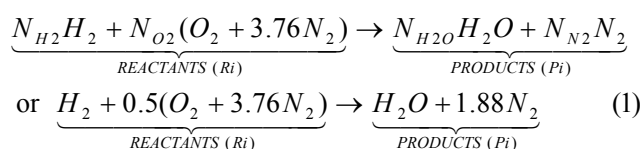
### Ideal Fuel-Cell Isothermal Reaction at Reference Temperature and Pressure

As already stated, it is possible to convert fuel chemical energy to electrical work directly, without heating the reaction products like during combustion, using an electrochemical cell, also known as *fuel cell*. It is a very simple device, like a fueled-battery or electrolysis-in-reverse. It consists of two porous metal electrodes with an electrolyte in-between, see Fig.1. The fuel, for example hydrogen molecules, after diffusing through one electrode will dissociate as positive ionic components by releasing electrons to that electrode. If an external load is connected to the electrodes, an electric current (electrons) will be flowing, and electrical work will be supplied to the load, while hydrogen fuel’s positive ions will be diffusing through the electrolyte, and at another electrode will be reacting with oxygen and electrons, forming water as the reaction product, see Fig.1.

Actual process may be deferent for different types of electrodes (anode and cathode) and electrolyte. The high efficiency of the fuel cell results from the electrochemical process where the energy of binding reactants' molecules, is converted directly to electrical work, imparted by electrons that move in the cell's external circuit. This is in contrast to conversion of the same energy during combustion to chaotic thermal motion, i.e. heating of combustion products' molecules, accompanied with substantial irreversibility and loss of work potential.

The maximum efficiency and work from a fuel cell is limited, according to the Second Law of Thermodynamics, to the decrease of the *Gibbs free energy* of the reactants ( $R_i$ ), as they form products ( $P_i$ ) in the electrochemical reaction. The difference between reactants and products' *Gibbs free energies* is very close to the fuel heating value  $Q_{HV}$ , so that fuel cell theoretical energy-conversion efficiency, in limit, is close to 100% if the process is conducted at constant pressure and temperature, and without dissipative heating of the products. In practice, with finite reaction rates, accompanied with dissipative heating and need for cooling to maintain reaction at as constant temperature as required, the efficiency is lower than maximum possible, but above 40 or even above 50 %, which is still substantially higher than usual heat-engine's efficiencies given in Table I, along with efficiencies of other energy conversion processes to mechanical or electrical work [2, 3].

For one kilo-mole of hydrogen-fuel ( $N_{H_2}=1 \text{ kmol}$ ) with theoretical oxygen (i.e. theoretical air) the chemical reaction is:



**TABLE III: Different molar properties for hydrogen reaction [1]**

Component	$\bar{h}_o \left[ \frac{kJ}{kmol} \right]$	$\bar{s}^o \left[ \frac{kJ}{kmolK} \right]$	$\bar{h}^{o_f} \left[ \frac{kJ}{kmol} \right]$	$\bar{g}^{o_f} \left[ \frac{kJ}{kmol} \right]$	$M \left[ \frac{kg}{kmol} \right]$
Hydrogen ( $H_2$ )	8468	130.574	0	0	2.016
Oxygen ( $O_2$ )	8682	205.033	0	0	31.999
Nitrogen ( $N_2$ )	8669	191.502	0	0	28.013
Water liquid $H_2O(g)$	9904	188.72	-241820	-228590	18.015
Water vapor $H_2O(l)$		69.92	-285830	-237180	18.015

NOTE: All values are for 298 K temperature. Entropy ( $s$ ) and free *Gibbs* energy ( $g$ ) values are for 298 K and 1 atm. Universal molar ideal-gas constant  $R_u=8314 \text{ kJ/kmol}$

Where number of moles  $N_{H_2}=1$ ,  $N_{O_2}=0.5$ ,  $N_{H_2O}=1$ , and  $N_{N_2}=3.76N_{O_2}=1.88$ , for hydrogen, oxygen, water and nitrogen, respectively. The molar numbers and mixture fraction ratios are summarized in Table II, while characteristic molar properties are given in Table III [1].

**TABLE II: Reactants and products' molar numbers and mixture fraction ratios**

Components $R P_i$		$N_{R P_i}$ $\left[ \frac{kmol_{R_i}}{kmol_{H_2}} \right]$	$Y_{R P_i}$
Reactants ( $R_i$ )	Hydrogen ( $H_2$ )	1	1
	Oxygen in air ( $O_2$ )	0.5	0.5/2.38
	Nitrogen in air ( $N_2$ )	1.88	1.88/2.38
Products ( $P_i$ )	Nitrogen ( $N_2$ ) [with $H_2O(g)$ ]	1.88	1.88/2.88
	Water $H_2O(g)$	1	1/2.88
or	Water $H_2O(l)$	1	1
Products ( $P_i$ )	Nitrogen ( $N_2$ ) [with $H_2O(l)$ ]	1.88	1

Note, that at the reference temperature (298 K) and reference pressure (1 atm), water is in liquid form, but the water properties for reference state are given for both, vapor-gas(g) and liquid(l) forms. The results for hydrogen reaction are given below for the both cases: when product water is in the vapor-gas(g) form, like in atmosphere (but extrapolated as ideal-gas at 1 atm), and when product water is in condensed liquid form(l), like in lakes.

Maximum possible reversible work is [1]:

$$W_{rev\_max} = \left. \begin{aligned} & \sum_R N_{Ri} \cdot \{ \bar{h}^o_{f,Ri} + \Delta \bar{h}_{Ri} - T_o [\bar{s}^o_{Ri} - R_u \ln(y_{Ri} P_r)] \} \\ & - \sum_P N_{Pi} \{ \bar{h}^o_{f,Pi} + \Delta \bar{h}_{Pi} - T_o [\bar{s}^o_{Pi} - R_u \ln(y_{Pi} P_r)] \} \end{aligned} \right\} = \left\{ \begin{aligned} & 2.302 \times 10^5 \text{ (g)} \\ & 2.362 \times 10^5 \text{ (l)} \end{aligned} \right\} \frac{kJ}{kmol H_2} \quad (2)$$

Where,  $N_{Ri}$  is mole number;  $\bar{h}^o_{f,Ri}$  is molar, reference enthalpy of compound formation (zero for stable elements);  $\Delta \bar{h}_{Ri}$  is sensible molar enthalpy increase from reference temperature;  $\bar{s}^o_{Ri}$  is absolute molar entropy at any relevant  $T$  and reference pressure  $P_o = 1 \text{ atm}$ ;  $R_u$  is the universal molar gas constant;  $y_{Ri} = N_{Ri} / N_{R,mixture}$  is molar fraction ratio in a mixture; and  $P_r$  is mixture-to-reference-pressure ratio, for a reactant ( $Ri = \{H_2, \text{air}[O_2, N_2]\}$ ), and similarly for product ( $Pi = \{H_2O, N_2\}$ )  $i$ -th component. Note,  $y_{H_2O(l)} = 1$  for product water in liquid form and it will not influence product mixture pressure of gaseous components. If all reactant and product components are at the reference temperature and atmospheric pressure each (i.e.,  $y_{Ri} = y_{Pi} = 1, P_r = 1$ ), then the above equation is simplified by using the molar *Gibbs* free energy of formation,  $\bar{g}^o_{f,Ri/Pi}$ , as:

$$\begin{aligned} W_{rev\_gf} &= \sum_R N_{Ri} \cdot \{ \bar{g}^o_{f,Ri} \} - \sum_P N_{Pi} \{ \bar{g}^o_{f,Pi} \} \\ &= \left\{ \begin{aligned} & -g_{f,H_2O(g)} \\ & -g_{f,H_2O(l)} \end{aligned} \right\} \\ &= \left\{ \begin{aligned} & 2.286 \times 10^5 \text{ (g)} \\ & 2.372 \times 10^5 \text{ (l)} \end{aligned} \right\} \frac{kJ}{kmol H_2} \quad (3) \end{aligned}$$

Enthalpy of formation of water vapor per 1 kmol of hydrogen at reference temperature and pressure (298 K and 1 atm), also known as enthalpy of hydrogen combustion, or a fuel lower heating value (LHV) if the product water is in vapor-gas(g) form, and a fuel higher heating value, HHV, if the product water is in liquid(l) form, i.e.:

$$\begin{aligned} h_C = Q_{HV} &= \sum_R N_{Ri} \cdot \{ \bar{h}^o_{f,Ri} \} - \sum_P N_{Pi} \{ \bar{h}^o_{f,Pi} \} \\ &= \left\{ \begin{aligned} & -\bar{h}^o_{f,H_2O(g)} \\ & -\bar{h}^o_{f,H_2O(l)} \end{aligned} \right\} = \left\{ \begin{aligned} & LHV \\ & HHV \end{aligned} \right\} \\ &= \left\{ \begin{aligned} & 2.418 \times 10^5 \text{ (g)} \\ & 2.850 \times 10^5 \text{ (l)} \end{aligned} \right\} \frac{kJ}{kmol H_2} \quad (4) \end{aligned}$$

Then ideal, limiting efficiency of a hydrogen fuel-cell will be (Eq.5):

$$\eta_{th\_FC\_mix} = \frac{W_{rev\_mix}}{Q_{HV}} = \left\{ \begin{aligned} & 95.2\% \text{ (g)} \\ & 82.6\% \text{ (l)} \end{aligned} \right\} \quad (5)$$

for product mixture at 1 atm ( $y_{Pi} \leq 1$ ); or

$$\begin{aligned} \eta_{th\_FC\_gf} &= \frac{W_{rev\_gf}}{Q_{HV}} = \left\{ \begin{aligned} & \frac{\bar{g}^o_{f,H_2O(g)}}{\bar{h}^o_{f,H_2O(g)}} \\ & \frac{\bar{g}^o_{f,H_2O(l)}}{\bar{h}^o_{f,H_2O(l)}} \end{aligned} \right\} \\ &= \left\{ \begin{aligned} & 94.5\% \text{ (g)} \\ & 83.0\% \text{ (l)} \end{aligned} \right\} \quad (6) \end{aligned}$$

if  $y_{Pi} = 1$  for every  $Pi$  component

Note a large difference of 12.6% (Eq. 5) between ideal hydrogen fuel-cell efficiencies when product water is in gas(g) and liquid(l) forms, due to latent heat of water vaporization and difference in water entropy between vapor and liquid forms. The corresponding percentage difference is smaller for other hydrocarbon fuels, since the carbon reaction does not produce water product. Furthermore, the corresponding efficiencies, Eq. (5) and (6), are somewhat different due to additional work obtained during reversible mixing of product components from atmospheric pressure each, like in Eq. (6), to the common atmospheric pressure, while the product components are at the lower partial pressure,  $y_{Pi}$ , like in Eq. (5). If those components are reversibly mixed into atmosphere, additional work is obtained. However, in practice no work is obtained during irreversible mixing.

### Ideal Adiabatic Combustion of Fuel with Theoretical-Air at Reference Temperature and Pressure

For the hydrogen fuel adiabatic combustion reaction, Eq. (1), maximum adiabatic combustion temperature,  $T_{ad}$ , is obtained by iteration (or trial-and-error) of energy balance equation (Eq.7):

$$\left. \begin{aligned} \sum_R N_{Ri} \cdot \{\bar{h}^o_{f,Ri} + [\Delta\bar{h}_{Ri}]\} &= \sum_P N_{Pi} \{\bar{h}^o_{f,Pi} + [\Delta\bar{h}_{Pi}]\}, \text{ or} \\ 0 &= \{\bar{h}^o_{f,H2O} + [\bar{h}_{H2O}(T_{ad}) - \bar{h}^o_{H2O}]\} + 1.88\{\bar{h}^o_{f,N2} + [\bar{h}_{N2}(T_{ad}) - \bar{h}^o_{N2}]\} \end{aligned} \right\} \Rightarrow T_{ad} = \begin{cases} 2525.6 \text{ K (g)} \\ 2881.0 \text{ K (l)} \end{cases} \quad (7)$$

Note, for  $T_{ad(g)}=2525.6 \text{ K}$  water vapor and nitrogen enthalpies are 110251 and 83921  $\text{kJ/kmol}$ , respectively, and for  $T_{ad(l)}=2881.0 \text{ K}$ , they are 129662 and 97005  $\text{kJ/kmol}$ , respectively.

Ideal adiabatic combustion with theoretical air is an irreversible process with the following entropy generation:

$$S_{comb\_gen} = \sum_P N_{Pi} [\bar{s}^o_{Pi} - R_u \ln(y_{Pi} P_r)] - \sum_R N_{Ri} [\bar{s}^o_{Ri} - R_u \ln(y_{Ri} P_r)] = \begin{cases} 178.65 \text{ (g)} \\ 194.47 \text{ (l)} \end{cases} \frac{\text{kJ}}{\text{K} \cdot \text{kmol } H_2} \quad (8)$$

Then the work lost due to entropy generation (i.e. combustion irreversibility) is:

$$\begin{aligned} W_{comb\_loss} &= T_o \cdot S_{comb\_gen} \\ &= \begin{cases} 5.324 \times 10^4 \text{ (g)} \\ 5.810 \times 10^4 \text{ (l)} \end{cases} \frac{\text{kJ}}{\text{kmol } H_2} \end{aligned} \quad (9)$$

And combustion *Second Law* (i.e., work availability, or exergy) efficiency:

$$\eta_{comb\_II} = 1 - \frac{W_{comb\_loss}}{Q_{HV}} = \begin{cases} 78.0\% \text{ (g)} \\ 79.0\% \text{ (l)} \end{cases} \quad (10)$$

Actually, it is more appropriate to evaluate combustion *Second Law* efficiency with reference to the maximum fuel work availability,  $W_{rev\_max}$ ,

Eq. (2), than the fuel heating value  $Q_{HV}$ , Eq. (4), i.e.:

$$\eta_{comb\_II\_mod} = 1 - \frac{W_{comb\_loss}}{W_{rev\_max}} = \begin{cases} 76.7\% \text{ (g)} \\ 75.5\% \text{ (l)} \end{cases} \quad (11)$$

### Ideal Heat-Engine Cycle Analysis

Heat engines are devices undergoing thermo-mechanical cycles, similar to one on Fig. 2, with mechanical expansion (turbine,  $W_T$ ) and compression ( $W_C$ ) net-work ( $W = W_T - W_C = Q_h - Q_o$ ), obtained as difference between the heat transferred to the engine from high temperature heat reservoir (at  $T_h$ ) and rejected to a low temperature heat reservoir (at  $T_o$ ), thus converting part of thermal energy into mechanical work. The combustion process itself is an irreversible one, where chemical energy (electro-chemical energy binding reactants' molecules) is chaotically released during combustion, i.e.

converted in 'chaotic' thermal energy of products' molecules, after which it cannot be fully transferred into useful work. The *Second Law of Thermodynamics* limits the maximum amount of work that could be obtained from thermal energy between two thermal reservoirs at different temperatures, hot  $T_h$ , and cold  $T_o$ , by using ideal, reversible *Carnot cycle*, see Fig. 2, with thermal

efficiency (Eq. 12):

$$\begin{aligned} \eta_{th,Tad,max} &= \frac{W}{Q_h} = \frac{Q_h - Q_o}{Q_h} \\ &= 1 - \frac{T_o}{T_h} \Bigg|_{T_o=298\text{K}, T_h=T_{ad}=\begin{cases} 2525.6\text{K (g)} \\ 2881.0\text{K (l)} \end{cases}} \\ &= \begin{cases} 88.2\% \text{ (g)} \\ 89.7\% \text{ (l)} \end{cases} \end{aligned} \quad (12)$$

The maximum efficiency is achieved if heat is available at the highest possible temperature  $T_h$ , and released at the lowest possible temperature  $T_o$ . However, the both temperatures are limited by the fact that a fuel combustion is performed using oxygen from ambient air, resulting in maximum stoichiometric-combustion, so called adiabatic temperature,  $T_{ad}$ , which is for most hydrocarbon fuels about 2400 K (or about 2000 °C). For pure hydrogen  $T_{ad(g)}=2526 \text{ K}$  and  $T_{ad(l)}=2801 \text{ K}$ , see Eq.(7). A part of the heat supplied at high temperature  $T_h$ , must be released to the surroundings at lower temperature, say  $T_o = 25^\circ\text{C} = 298 \text{ K}$ . Using the adiabatic temperature (Eq.7) results in a rather high ideal *Carnot* efficiency, see Eq. (12) and Fig. 2. However these efficiencies are misleading as explained next.

In fact, the fuel heating-value energy,  $Q_{HV}$ , is not all available at the adiabatic temperature of the products, but is distributed over their variable temperature range from initial surrounding temperature before combustion  $T_o$ , to final adiabatic temperature  $T_{ad}$ , see Fig. 3. If a single *Carnot* cycle is used at constant temperature  $T_h < T_{ad}$ , then only fraction  $(T_{ad} - T_h)/(T_{ad} - T_o)$  of the fuel heating value will be used, resulting in reduced maximum *Carnot*

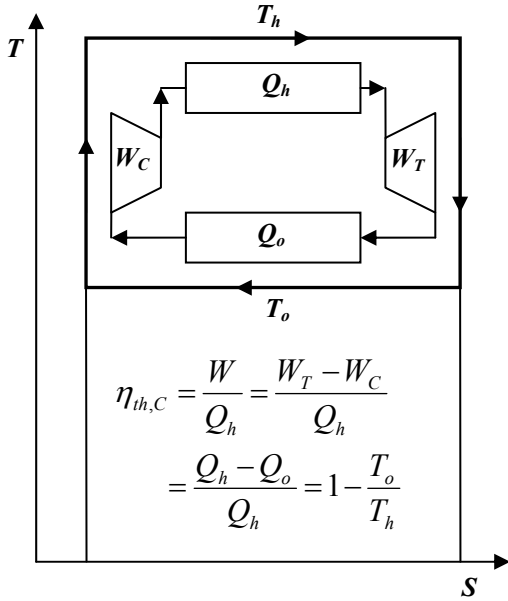


Figure 2: Heat engine ideal *Carnot* cycle

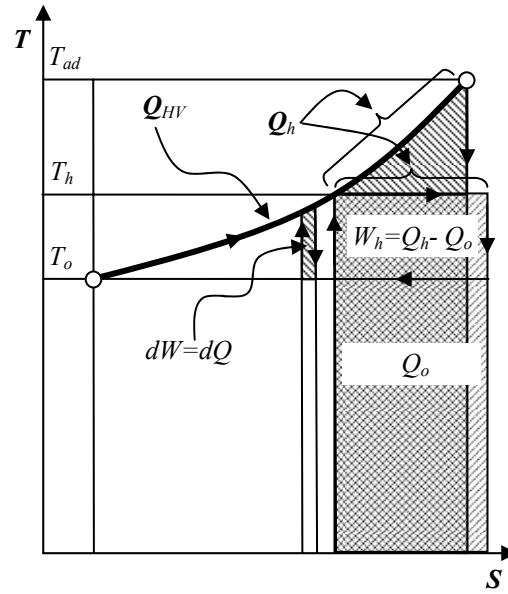


Figure 3: Heat engine, constant and variable temperature, ideal *Carnot* cycle

efficiency (assuming constant specific heats), see Eq.(13):

$$\eta_{th,Th} = \left(1 - \frac{T_o}{T_h}\right) \cdot \left(\frac{T_{ad} - T_h}{T_{ad} - T_o}\right) \Bigg|_{\max \text{ for } T_h = \sqrt{T_{ad}T_o}}$$

$$= \frac{\sqrt{T_{ad}/T_o} - 1}{\sqrt{T_{ad}/T_o} + 1} \Bigg|_{T_o=298K, T_{ad}=\begin{cases} 2525.6K(g) \\ 2881.0K(l) \end{cases}}$$

$$= \begin{cases} 48.9\%(g) \\ 51.3\%(l) \end{cases} \quad (13)$$

The efficiency, Eq.(13), may be further increased by employing a large number (infinite in limit) of ideal *Carnot* engines operating at different temperatures (with  $dW=dQ$ ), or with variable hot temperature heat exchange, see Fig. 3. Assuming constant specific heat of combustion products, and after integration, the variable hot-temperature *Carnot* cycle yields the maximum possible combustion-products-to-work conversion efficiency:

$$\eta_{th,T_{var,max}} = \left(1 - \frac{\ln(T_{ad}/T)}{(T_{ad}/T) - 1}\right) \Bigg|_{T_o=298K, T_{ad}=\begin{cases} 2525.6K(g) \\ 2881.0K(l) \end{cases}}$$

$$= \begin{cases} 71.4\%(g) \\ 73.8\%(l) \end{cases} \quad (14)$$

**Conclusion**

Summary of the most characteristic results are presented in Table IV for convenient comparison.

**TABLE IV: Ideal fuel-cell, combustion and *Carnot* engine efficiencies**

Efficiencies	Eq. Nos.	Water is vapor-gas (g)	Water is liquid (l)	The (g)-(l) difference
$\eta_{th\_FC\_gf}$	(6)	94.5 %	83.0 %	11.5 %
$\eta_{comb\_II}$	(10)	78.0 %	79.0 %	-1.0 %
$\eta_{th,T_{var,max}}$	(14)	71.4 %	73.8 %	-2.4 %
$\eta_{th\_FC\_g}^-$ $\eta_{th,T_{var,max}}$	(6)- (14)	23.1 %	9.2 %	13.9 %

Less than 7% difference between the corresponding combustion efficiencies, Eqs. (10) and variable temperature *Carnot* efficiencies, Eq. (14), are due to the assumptions that product specific heats are not dependent on temperature, and over-all entropy change of reactant and product components are not fully accounted in Eq. (14).

(14)

Due to engine material property limitations and other unavoidable irreversibilities, it is impossible to reach the ideal *Carnot* efficiency [2, 3]. Different actual heat engines undergo similar but different cycles, depending on the system design. For example, internal combustion engines undergo the *Otto* cycle with gasoline fuel and the *Diesel* cycle with diesel fuel, while the steam and gas turbine power plants undergo the *Rankine* and *Brayton* cycles, respectively [1].

However, with improvements in material properties, effective component cooling, regenerative heating, and combining gas and steam turbine systems, more than 50% efficiencies are being achieved, which is a substantial improvement over usual 35%, see Table I. The ideal *Carnot* cycle is an important reference to guide researchers and engineers to better understand limits and possibilities for new concepts and performance improvements of real heat engines.

The fuel energy conversion to mechanical work in heat engines is limited by ideal *Carnot*-cycle efficiency (for most fuels about 70% limit; close to 80% for pure hydrogen), due to irreversibility of combustion process alone. However, there is a device capable of controlling electron-energy exchange by re-routing electrons from fuel molecules via external load, thus departing process excess-energy in form of work, before the reactants' atoms are isothermally regrouped into products molecules. The electrical power is obtained in more controlled, in-limit a reversible electrochemical reaction, without need of heating of reaction products, and without moving

machinery and associated vibrations and noise. These devices, known as fuel-cells, work like fueled-batteries or electrolysis-in-reverse, with much higher conversion efficiencies than heat engines (for most fuels close to 100% limit; about 95% and 83% for pure hydrogen fuel if product water is in vapor and liquid forms, respectively). The practical energy conversion efficiencies are usually half of their theoretical limits, namely about 35% and 50% for heat engines and fuel cells respectively. Regardless of the fuel-cells' much higher efficiencies and mechanical simplicity, further developments are needed to overcome their limitations in low power density and competitive cost.

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