

## Topics

- Adiabatic Combustion
- Adiabatic Flame Temperature Example
- Combustion Efficiency
- Second and First Law Efficiencies Contrasted
- Example Problem

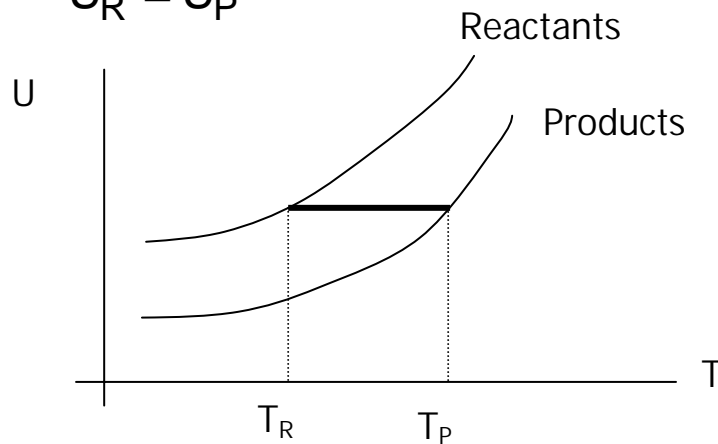
## 1. The Case of Adiabatic Combustion

Here it is assumed that there is no heat transfer of significance during the combustion process. Hence adiabatic.

## Constant Volume Adiabatic Combustion

$$Q = 0 = \Delta U$$

$$U_R = U_P$$

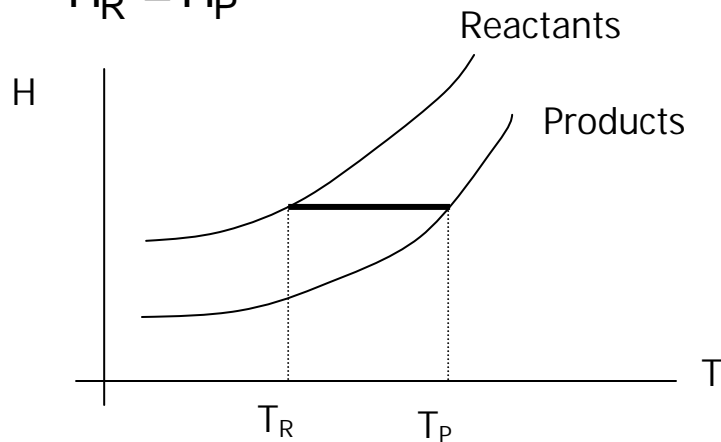


The temperature  $T_P$  is called the adiabatic flame temperature for constant pressure combustion.

## Constant Pressure Adiabatic Combustion

$$Q = 0 = \Delta H$$

$$H_R = H_P$$



The temperature  $T_P$  is called the adiabatic flame temperature for constant pressure combustion.

Example with EES -- Just a modification of a previous Example

"Adiabatic Flame Temperatures - Propane Combustion"

"Equation of Combustion of Propane in Air



$$T_1 = 298.15$$

"Calculations will be based on mass of 1 kg  $\text{C}_3\text{H}_8$ "

$$m_{\text{C}_3\text{H}_8} = 1$$

$$m_{\text{O}_2} = 5 \cdot \text{MOLARMASS}(\text{O}_2) / \text{MOLARMASS}(\text{C}_3\text{H}_8)$$

$$m_{\text{CO}_2} = 3 \cdot \text{MOLARMASS}(\text{CO}_2) / \text{MOLARMASS}(\text{C}_3\text{H}_8)$$

$$m_{\text{H}_2\text{O}} = 4 \cdot \text{MOLARMASS}(\text{H}_2\text{O}) / \text{MOLARMASS}(\text{C}_3\text{H}_8)$$

$$m_{\text{N}_2} = 5 \cdot 3.773 \cdot \text{MOLARMASS}(\text{N}_2) / \text{MOLARMASS}(\text{C}_3\text{H}_8)$$

## "Enthalpy of Products and Reactants"

$$\begin{aligned}H_R &= \\m_{C_3H_8} &\cdot ENTHALPY(C_3H_8, T=T_1) + m_{O_2} \cdot ENTHALPY(O_2, T=T_1) \\&+ m_{N_2} \cdot ENTHALPY(N_2, T=T_1) \\H_P &= \\m_{CO_2} &\cdot ENTHALPY(CO_2, T=T_2) + m_{H_2O} \cdot ENTHALPY(H_2O, T=T_2) \\&+ m_{N_2} \cdot ENTHALPY(N_2, T=T_2) \\DELTA_H &= H_P - H_R\end{aligned}$$

"This gets adiabatic flame temp. for constant pressure combustion."

$$DELTA_H = 0$$

## "Internal Energy of Products and Reactants"

$$\begin{aligned}U_R &= \\m_{C_3H_8} &\cdot INTENERGY(C_3H_8, T=T_1) + m_{O_2} \cdot INTENERGY(O_2, T=T_1) \\&+ m_{N_2} \cdot INTENERGY(N_2, T=T_1) \\U_P &= \\m_{CO_2} &\cdot INTENERGY(CO_2, T=T_3) + m_{H_2O} \cdot INTENERGY(H_2O, T=T_3) \\&+ m_{N_2} \cdot INTENERGY(N_2, T=T_3) \\DELTA_U &= U_P - U_R\end{aligned}$$

"This gets adiabatic flame temperature for constant vol. combustion"

$$DELTA_U = 0$$

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## 2. Combustion Efficiency

Here's another efficiency to learn. The combustion process in IC engines is never perfectly complete.

For example, very small amounts of unburned fuel can hide out in crevices.

Or, more likely, the combustion process produces CO or soot, or any other product of partial combustion.

Hence, not all the chemical energy in the fuel is released by the combustion process.

Let  $H_P$  be the enthalpy of the products of combustion and  $H_R$  the enthalpy of the reactants -- both evaluated at ambient temperature, and one atmosphere.

Hence

$$H_P = \sum_{\text{products}} n_i \Delta \tilde{h}_{f,i}^{\circ} \quad \text{and} \quad H_R = \sum_{\text{reactants}} n_i \Delta \tilde{h}_{f,i}^{\circ}$$

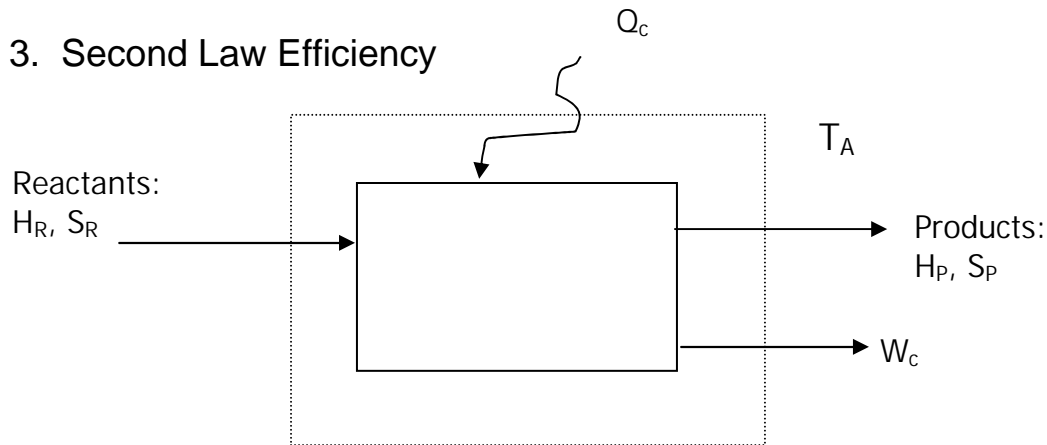
where  $\Delta \tilde{h}_{f,i}^{\circ}$  represents the enthalpy of formation and  $n_i$  the number of moles.

- The actual chemical energy actually released is  $H_R - H_P$ .
- The total chemical energy that could be released is  $m_f Q_{HV}$ .

Therefore the combustion efficiency is

$$\eta_c = \frac{H_R - H_P}{m_f Q_{HV}}$$

### 3. Second Law Efficiency



The picture shows what happens during one engine cycle.

First Law of Thermo:

$$Q_C - W_C + \sum_{\text{in}} mh - \sum_{\text{out}} mh = 0$$

$$Q_C - W_C = \sum_{\text{out}} mh - \sum_{\text{in}} mh = \Delta H = H_P - H_R$$

Second Law of Thermo ( $s$ , entropy per unit mass of P & R)

$$\frac{Q_C}{T_A} + \sum_{\text{in}} ms - \sum_{\text{out}} ms + \Delta S_{\text{gen}} = 0$$

If we say there is not any entropy generated - reversible case - AND it must be true that  $T_A = T_R = T_P$ .

$$\frac{Q_C}{T_A} = \sum_{\text{out}} ms - \sum_{\text{in}} ms = S_P - S_R$$

$$Q_C = T_A S_P - T_A S_R = T_A \Delta S$$

So we can assume that this would correspond to the case where  $W_C$  is maximized.

Substitute into the first law,

$$T_A \Delta S - W_{c,\max} = \Delta H$$

$$-W_{c,\max} = \Delta H - T_A \Delta S = \Delta B$$

B is the steady flow energy availability function. It depends on the ambient conditions and the fluid properties of the reactant and product streams.

Since we have agreed that the fluid streams are at ambient temperature,

$$\Delta B = (H_P - T_P S_P) - (H_R - T_R S_R)$$

in other words for this particular situation  $\Delta B = \Delta G$  where the Gibbs Free Energy  $H - TS$  is a property, or state variable.

Recall that we had  $-\Delta H = m_f Q_{HV}$ . In the same way we let

$$-\Delta B = -\Delta G = m_f a$$

Where  $a$  might be called the available energy of combustion. Note it takes into account the difference in entropy in products and reactants.

The second law efficiency is

$$\eta_a = \frac{\text{Work per cycle}}{\text{Max Possible Work per cycle}} = \frac{W_c}{W_{c,\max}} = \frac{W_c}{m_f a}$$

Contrast with the first law efficiency

$$\eta_f = \frac{\text{Work per cycle}}{\text{Chem Energy per cycle}} = \frac{W_c}{m_f Q_{LHV}}$$

What we have called the fuel conversion efficiency.

The second law or availability efficiency is

- Not as easy to evaluate as the first law efficiency. But this evaluation opens the door to availability analysis, which is a fruitful way of looking at the different factors which effect efficiency with an eye to improvement.
- For hydrocarbon fuels  $\Delta g$  and  $\Delta h$  are close. Consequently the first and second law efficiencies will be close. We will follow the text and focus on first law efficiencies.

There is yet another efficiency which comes into play at times. It takes into account the incomplete combustion process. It is called the thermal conversion efficiency.

$$\eta_t = \frac{W_c}{\eta_c m_f Q_{LHV}}$$

Apparently,  $\eta_f = \eta_t \eta_c$ .

### Example Problem (3.6)

The brake fuel conversion efficiency is 0.3. The mechanical efficiency is 0.8. The combustion efficiency is 0.94. The heat losses to the coolant and oil are 60 kW. The fuel chemical energy entering the engine per unit time

$$\dot{m}_f Q_{HV} = 190 \text{ kW} .$$

What percentage of this energy becomes

- a) brake work or power
- b) friction work or power
- c) heat losses
- d) exhaust chemical energy
- e) exhaust sensible energy.

Draw a diagram with the engine in a CV and these quantities indicated.

Important: Let's assume that the friction work and the heat losses do not overlap. (After all one is work, and the other heat)

The sensible energy of the exhaust is what's left in the exhaust after the exhaust chemical energy is removed.