Power Plant Engineering

Lecture 4

Fuels and Combustion

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Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Explain the concept of reference state and reference values and their importance in thermochemical calculations.

ii. Analyze the composition and behavior of reacting mixtures using mole fractions, mass fractions, and chemical equilibrium principles.

iii. Define the enthalpy of formation and use it to compute the enthalpy changes of reactions.

iv. Apply the First Law of Thermodynamics to closed and open reacting systems to evaluate energy changes.

v. Determine the adiabatic flame temperature for combustion reactions under idealized conditions.

vi. Distinguish between higher and lower heating values of fuels and describe standard methods for their experimental determination.

Content

1. Reference State and Reference Values

- Thermodynamic properties like enthalpy, entropy, and internal energy are relative-not absolute.
- The values cannot be measured directly, and they are calculated from measurable properties using the relations between thermodynamic properties.
- However, those relations give the changes in properties, not the values of properties at specified state.
- Reference state and reference values are foundational for calculating thermodynamic properties.
- They provide a baseline against which we measure and compare thermodynamic properties like enthalpy, entropy, and internal energy.

1. Reference State and Reference Value Cont…

- A reference state is a defined condition (temperature, pressure, phase) used as a baseline for measuring thermodynamic properties [1].
- Standard reference state is the most stable form of an element at 1 atm and 25°C.
- Reference states are conventions, not physical truths.
- Commonly used reference conditions:
  - ✓Temperature: 25°C (298.15 K)
  - ✓Pressure: 1 atm (101.325 kPa)
  - ✓Phase: Most stable form at the reference temperature and pressure

1. Reference State and Reference Value

Cont…

Example:

- ✓For oxygen (O_2), reference state is gaseous O_2 at 25°C and 1 atm.
- ✓For water (H_2O), the state saturated liquid at 0.01°C is taken as the reference state, and the internal energy and entropy are assigned zero values at that sate.
- ✓For refrigerant 134a, the state saturated liquid at -40°C is taken as the reference state, and the enthalpy and entropy are assigned zero values at that state.

- In thermodynamics, the focus is on changes in properties, and the reference chosen has no consequences in the calculations.

1. Reference State and Reference Value Cont…

- A Reference Value is the numerical value assigned to a specific thermodynamic property at the reference state [1].

- The most important reference values are reference enthalpy (h_o) and reference entropy (s_o).

Example:

- ✓Entropy of liquid water at 0°C = 0 (by convention in steam tables).
- ✓Standard enthalpy of formation of O_2 (g) at 298 K = 0 kJ/mol.

2. Reacting Mixtures

- A reacting mixture is a system containing two or more chemical species that undergo a chemical reaction.
- It is a combination of chemical species undergoing a chemical reaction, typically involving combustion or synthesis.
- A chemical reaction changes the molecular identity of the substances involved.
- This transformation releases or absorbs a significant amount of energy, primarily as heat and is used to understand energy release, fuel efficiency, and environmental impact in engines, furnaces, and chemical reactors.
- When chemical reaction occurs, reactants disappear and products are formed, so differences can not be calculated for all substances involved.

2. Reacting Mixtures

Cont…

- An enthalpy datum for the study of reacting systems can be established by assigning arbitrarily a value of zero to the enthalpy of the stable elements at a state called the standard reference state and defined by $T_{ref} = 298\, K (25^o C)$ and $P_{ref} = 1\, atm$ [2].
- Enthalpy values can be assigned to compounds for use in the study of reacting systems.
- Reacting mixtures contain:
  - ✓ Chemical species: e.g., O_2, CO_2, CH_4, H_2O
  - ✓ Mixture composition: Mass fraction, mole fraction, molar concentration
  - ✓ Reaction stoichiometry: A balanced chemical equation

3. Enthalpy of Formation

- Enthalpy of formation is a fundamental property used to calculate energy changes in chemical reactions.
- The enthalpy of formation ($\bar{h}_f^o$) is the energy released or absorbed when the compound is formed from its elements, the compound and elements all being in their most stable reference states at standard conditions (298.15 K, 1 bar, 1 M solution for solutes) [3].
- During a chemical reaction, some chemical bonds that bind the atoms into molecules are broken, and new ones are formed.
- The chemical energy associated with these bonds, in general, is different for the reactants and the products.

3. Enthalpy of Formation

Cont…

- A process that involves chemical reactions will involve changes in chemical energies, which must be accounted for in an energy balance.
- Assuming that the atoms of each reactant remains intact (no nuclear reactions) and disregarding any changes in kinetic and potential energies, the energy change of a system during a chemical reaction will be due to a change in state and a change in chemical composition [4]. That is,

$$\Delta E_{sys} = \Delta E_{state} + \Delta E_{chem}$$

- In thermodynamics we are concerned with the changes in the energy of a system during a process, and not the energy values at the particular states.

3. Enthalpy of Formation

Cont…

- Any state can be chosen as the reference state and assign a value of zero to the internal energy or enthalpy of a substance at that state.
- It is necessary to have a common reference state for all substances.
- The chosen reference state is 298.15 K, and 1 atm, which is known as the standard reference sate.
- Property values at the standard reference state are indicated by a superscript "o" (such as h^o and u^o)
- When analyzing reacting systems, we must use property values relative to the standard reference state.

3. Enthalpy of Formation

Cont…

- However, it is not necessary to prepare a new set of property tables for this purpose.
- We can use the existing tables by subtracting the property values at the standard reference state from the values at the specified state.
- The ideal-gas enthalpy of N_2 at 500K relative to the standard reference state, for example, is [4]

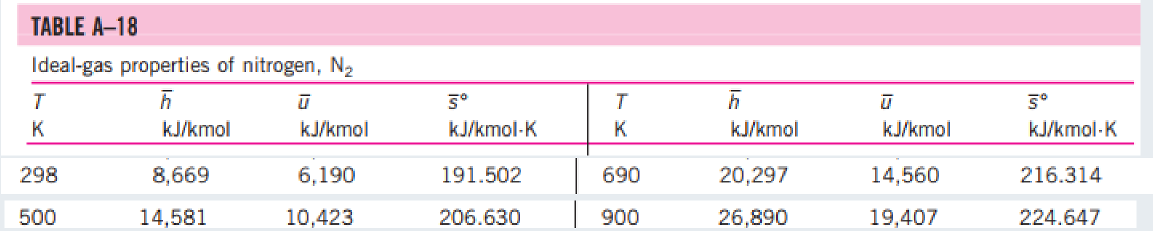


TABLE A–18

Ideal-gas properties of nitrogen, N_2

T K	$\bar{h}$ kJ/kmol	$\bar{u}$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol·K	T K	$\bar{h}$ kJ/kmol	$\bar{u}$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol·K
298	8,669	6,190	191.502	690	20,297	14,560	216.314
500	14,581	10,423	206.630	900	26,890	19,407	224.647

$$Enthalpy = \bar{h}_f^o + \left(\bar{h} - \bar{h}^o\right) \, (kJ/kmol\ )$$

$$\bar{h}_{500K} - \bar{h}^o = 14{,}581 - 8669 = 5912 \, kJ/kmol$$

3. Enthalpy of Formation

Cont…

- The enthalpy of formation of the elements found naturally as diatomic elements, such as nitrogen, oxygen, and hydrogen, is defined to be zero.

Table 1: Enthalpy of Formation at 298 K and 1 atm [4]

Substance	Formula	M	$\bar{h}_f^o$ kJ/kmol
Air		29	0
Oxygen	O_2	32	0
Nitrogen	N_2	28	0
Carbon Dioxide	CO_2	44	-393,520
Carbon Monoxide	CO	28	-110,530
Water (vapor)	H_2Ovap	18	-241,820
Water (liquid)	H_2Oliq	18	-285,830
Methane	CH_4	16	-74,850
Acetylene	C_2H_2	26	+226,730
Ethane	C_2H_6	30	-84,680
Propane	C_3H_8	44	-103,850
Butane	C_4H_{10}	58	-126,150
Octane (vapor)	C_8H_{18}	114	-208,450
Dodecane	$C_{12}H_{26}$	170	-291,010

3. Enthalpy of Formation

Cont…

- Enthalpy change will be different for different reactions, and it would be very desirable to have a property to represent the changes in chemical energy during a reaction.
- This property is the enthalpy of reaction, h_R, which is defined as the difference between the enthalpy of the products at a specified state and the enthalpy of the reactants at the same state for a complete reaction.
- For combustion processes, the enthalpy of reaction is usually referred to as the enthalpy of combustion, h_C, which represents the amount of heat released during a steady-flow combustion process when 1 kmol (or 1 kg) of fuel is burned completely at a specified temperature and pressure.

3. Enthalpy of Formation

Cont…

- Enthalpy of combustion:

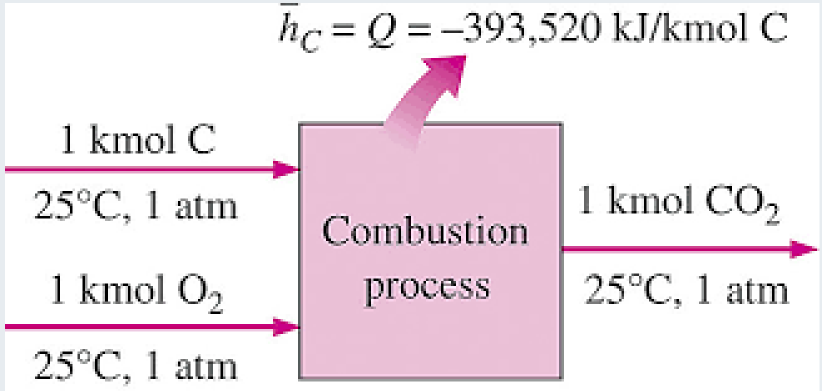
$$h_C = H_{Product} - H_{Reactant}$$

- A more practical approach would be to have a more fundamental property to represent the chemical energy of an element or a compound at some reference state.
- This property is the enthalpy of formation, $\bar{h}_f^o$, which can be viewed as the enthalpy of a substance at a specified state due to its chemical composition.
- To establish a starting point, we assign the enthalpy of formation of all stable elements (such as $O_2, N_2, H_2, and\ C$) a value of zero at the standard reference state of 298 K and 1 atm.

3. Enthalpy of Formation

Cont…

Example: Enthalpy of formation of CO_2



$$h_C = H_{Product} - H_{Reactant}$$

Figure 1: Enthalpy of Combustion, Combustion, Parente, A. (2011)
url:https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRIoIK7yznyqCRbTEuwYIXY3mJgjDrcYFjgF_o-58ga4FEPuETO

4. First Law Analysis of Reacting Systems

- The energy balance relations (the first law) are applicable to both reacting and non-reacting systems.
- However, chemically reacting systems involve changes in their chemical energy, and thus it is more convenient to rewrite the energy balance relations so that the changes in chemical energies are explicitly expressed.
- For a substance involved in a chemical reaction, its total enthalpy is the sum of its chemical energy (formation enthalpy) and its sensible energy relative to the standard state (25°C) [4].

$$h(T) = \bar{h}_f^o + [h(T) - h(298K)]$$

Where, $\bar{h}_f^o = enthalpy\ of\ formation\ (the\ chemical\ energy)\ at\ 25^oC, 1\ atm$

$[h(T) - h(298K)] = Sensible\ enthalpy\ change\ (the\ thermal\ energy)$

4. First Law Analysis of Reacting Systems Cont…

- Energy balance relations can be used for:
  - ✓ Steady flow systems
  - ✓ Closed systems

1. Steady Flow Systems

Let's consider the most common case: an open system, steady-flow, combustion chamber.

Assumptions:

- ✓ Steady-state, steady-flow ($\dot{m}_{in} = \dot{m}_{out}$).
- ✓ Negligible kinetic and potential energy changes.
- ✓ No work interaction ($W = 0$).

4. First Law Analysis of Reacting Systems Cont…

The general energy balance reduces to:

$$Q = H_{Prod} - H_{React}$$

Where:

$Q = Heat\ transfer\ from\ the\ system. If\ Q\ is\ negative, heat\ is\ lost.$

$H_{React} = Total\ enthalpy\ of\ the\ reactants\ entering$

$H_{Prod} = Total\ enthalpy\ of\ the\ products\ exiting$

To calculate H_{react} and H_{Prod}, we sum the total enthalpies of all components:

4. First Law Analysis of Reacting Systems Cont…

- Neglecting changes in kinetic and potential energies, $E_{in} = E_{out}$.
- For a chemically reacting steady-flow system:

$$Q_{in} + W_{in} + \sum n_r\left(\bar{h}_f^o + \left(\bar{h} - \bar{h}^o\right)\right)_r = Q_{out} + W_{out} + \sum n_p\left(\bar{h}_f^o + \left(\bar{h} - \bar{h}^o\right)\right)_p$$

- Where n_p and n_r represent the molal flow rates of the product p and the reactant r, respectively.

Reactant: Rate of net energy transfer in by heat, work and mass

Product: Rate of net energy transfer out by heat, work and mass

4. First Law Analysis of Reacting Systems **Cont…**

Per mole of fuel:

$$Q_{in} + W_{in} = Q_{out} + W_{out} + \sum N_p \left(\bar{h}_f^o + (\bar{h} - \bar{h}^o) \right)_p - \sum N_r \left(\bar{h}_f^o + (\bar{h} - \bar{h}^o) \right)_r$$

Where N_r and N_p represent the number of moles of the reactant r and the product p, respectively.

$$Q - W = \sum N_p \left(\bar{h}_f^o + (\bar{h} - \bar{h}^o) \right)_p - \sum N_r \left(\bar{h}_f^o + (\bar{h} - \bar{h}^o) \right)_r$$

$$Q - W = H_{prod} - H_{react} \quad (kJ/kmol\ fuel)$$

4. First Law Analysis of Reacting Systems Cont…

- If the enthalpy of combustion, $\bar{h}_c^o$, for a particular reaction is available, the steady-flow energy equation per mole of fuel can be expressed as

$$Q = \bar{h}_c^o + \sum N_p \left(\bar{h} - \bar{h}^o\right)_p - \sum N_r \left(\bar{h} - \bar{h}^o\right)_r$$

- The energy balance relations above are sometimes written without the work term since most steady-flow combustion processes do not involve any work interactions.

4. First Law Analysis of Reacting Systems **Cont…**

- A combustion chamber normally involves heat output but no heat input.
- Then the energy balance for a typical steady-flow combustion process becomes

$$Q_{out} = \sum N_r\left(\bar{h}_f^o + \left(\bar{h} - \bar{h}^o\right)\right)_r - \sum N_p\left(\bar{h}_f^o + \left(\bar{h} - \bar{h}^o\right)\right)_p$$

- It expresses that the heat output during a combustion process is simply the difference between the energy of the reactants entering and the energy of the products leaving the combustion chamber.

4. First Law Analysis of Reacting Systems Cont…

2. Closed Systems

- The general closed-system energy balance relation, $E_{in} - E_{out} = \Delta E_{System},$ can be expressed for a stationary chemically reacting closed system as:

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = U_{prod} - U_{react} \ \ (kJ/kmol\ fuel)$$

- To avoid using another property, the internal energy of formation, $\bar{u}_f^o$, we utilize the definition of enthalpy

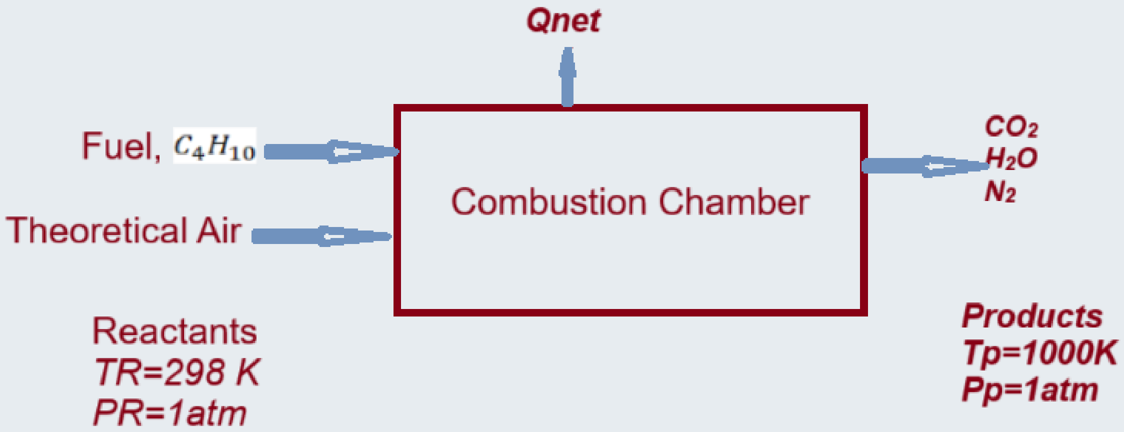
$$\left(\bar{u} = \bar{h} - P\bar{v} \ \ or\ \bar{u}_f^o + u - \bar{u} = \bar{h}_f^o + \bar{h} - \bar{h}^o - P\bar{v}\right)$$

$$Q - W = \sum N_p\left(\bar{h}_f^o + \left(\bar{h} - \bar{h}^o\right) - P\bar{v}\right)_p - \sum N_r\left(\bar{h}_f^o + \left(\bar{h} - \bar{h}^o\right) - P\bar{v}\right)_r$$

4. First Law Analysis of Reacting Systems **Cont…**

Example:

- Butane gas C_4H_{10} is burned in theoretical air as shown below. Find the net heat transfer per kmol of fuel.



- Balanced combustion equation:

$$C_4H_{10} + 6.5(O_2 + 3.76N_2) \rightarrow 4CO_2 + 5H_2O + 24.44N_2$$

4. First Law Analysis of Reacting Systems Cont…

$C_4H_{10} + 6.5(O_2 + 3.76N_2) \rightarrow 4CO_2 + 5H_2O + 24.44N_2$

The steady-flow heat transfer is

$$Q_{net} = H_P - H_R = \sum_{Products} N_e\left[\bar{h}_f^o + (\bar{h}_T - \bar{h}^o\right]_e - \sum_{Reactants} N_i\left[\bar{h}_f^o + (\bar{h}_T - \bar{h}^o\right]_i$$

Component	N_i (kmol/ kmol fuel)	$\bar{h}_f^o$ (kJ/kmol)	$\bar{h}_T$ (kJ/kmol)	$\bar{h}^o$ (kJ/kmol)	$N_i\left[\bar{h}_f^o + (\bar{h}_T - \bar{h}^o\right]_i$ kJ/kmol fuel
C_4H_{10}	1	-126,150	-	-	-126,150
O_2	6.5	0	8,682	8,682	0
N_2	24.44	0	8,669	8,669	0

Reactants: $T_R = 298K$

$$H_R = \sum_{Reactants} N_i\left[\bar{h}_f^o + (\bar{h}_T - \bar{h}^o\right]_i = -126{,}150 \frac{kJ}{Kmol\ C_4H_{10}}$$

4. First Law Analysis of Reacting Systems **Cont…**

$$C_4H_{10} + 6.5(O_2 + 3.76N_2) \rightarrow 4CO_2 + 5H_2O + 24.44N_2$$

Products: $T_P = 1000K$

Component	N_e (kmol/ kmol fuel)	$\bar{h}_f^o$ (kJ/kmol)	$\bar{h}_T$ (kJ/kmol)	$\bar{h}^o$ (kJ/kmol)	$N_e\left[\bar{h}_f^o + (\bar{h}_T - \bar{h}^o\right]_e$ kJ/kmol fuel
CO_2	4	-393,520	42,769	9,364	-1,440,460
H_2O	5	-241,820	35,882	9,904	-1,079,210
N_2	24.44	0	30,129	8,669	+524,482

$$H_P = \sum_{Products} N_e\left[\bar{h}_f^o + (\bar{h}_T - \bar{h}^o\right]_e = -1{,}995{,}188 \frac{kJ}{Kmol\ C_4H_{10}}$$

$$Q_{net} = H_P - H_R = -1{,}869{,}038 \frac{kJ}{Kmol\ C_4H_{10}}$$

5. Adiabatic Flame Temperature

- The chemical energy released during a combustion process either is:-
  - ✓ lost as heat to the surroundings or,
  - ✓ used internally to raise the temperature of the combustion products.
- The smaller the heat loss, the larger the temperature rise.
- In the limiting case of no heat loss to the surroundings (Q=0), the temperature of the products will reach a maximum, which is called the adiabatic flame or adiabatic combustion temperature of the reaction.

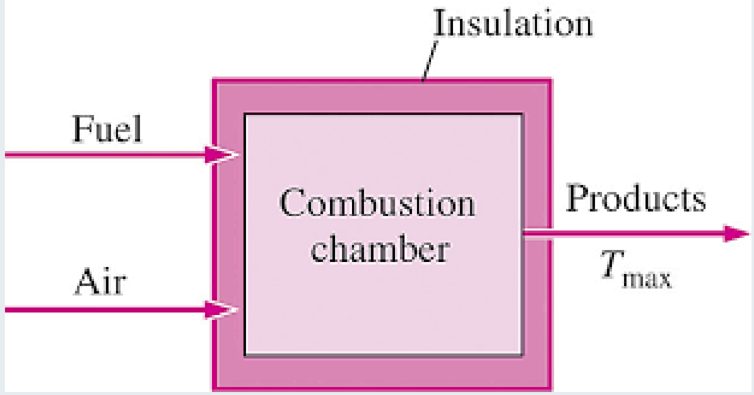


Figure 2: Adiabatic Flame Temperature, Bahaidarah, H. M. S. *Chemical Reactions.* url:https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcT_7i8qxqyTnaKTYLhKmj4_CptBa-Uk2sZFkW6NdXs6CyOWEnclnq9kau2SUR4uJy0EDHY&usqp=CAU

5. Adiabatic Flame Temperature

Cont…

- The Adiabatic Flame Temperature (AFT) is the maximum temperature achieved by a combustion process when [5]:
  - ✓ The reaction occurs adiabatically (no heat loss to surroundings).
  - ✓ The reactants are completely burned.
  - ✓ The products reach thermal equilibrium.
- In simpler terms, it is the maximum possible temperature achievable for a given fuel and oxidizer under specific conditions.
- Assumptions:
  - ✓ Adiabatic process
  - ✓ Complete combustion
  - ✓ Stoichiometric mixture
  - ✓ Excess air
  - ✓ Steady state, steady-flow

5. Adiabatic Flame Temperature

Cont…

- The importance of adiabatic flame temperature are:
  - ✓ It sets the upper temperature limit for engines (like rockets, jet engines, IC engines) and furnaces, which dictates material selection and cooling requirements. (Metallurgical limits)
  - ✓ It helps in calculating the theoretical maximum efficiency of a combustion process.
  - ✓ High temperatures promote the formation of thermal NOx; predicting AFT helps in designing low-NOx burners.

5. Adiabatic Flame Temperature

Cont…

- For a typical steady-flow combustion process:

$$Q_{out} = \sum N_r(\bar{h}_f^o + (\bar{h} - \bar{h}^o))_r - \sum N_p(\bar{h}_f^o + (\bar{h} - \bar{h}^o))_p$$

$$\sum N_r(\bar{h}_f^o + (\bar{h} - \bar{h}^o))_r = \sum N_p(\bar{h}_f^o + (\bar{h} - \bar{h}^o))_p$$

- For a typical closed combustion process

$$Q_{out} = \sum N_r(\bar{h}_f^o + (\bar{h} - \bar{h}^o) - R_u T)_r - \sum N_p(\bar{h}_f^o + (\bar{h} - \bar{h}^o) - R_u T)_p$$

$$\sum N_r(\bar{h}_f^o + (\bar{h} - \bar{h}^o) - R_u T)_r = \sum N_p(\bar{h}_f^o + (\bar{h} - \bar{h}^o) - R_u T)_p$$

T - adiabatic flame temperature

5. Adiabatic Flame Temperature Cont…

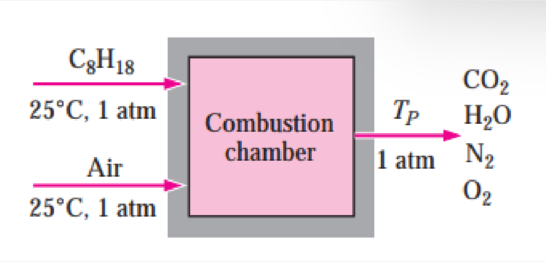
Example:

Liquid octane (C_8H_{18}) enters the combustion chamber of a gas turbine steadily at 1 atm and 25°C, and it is burned with air that enters the combustion chamber at the same state. Determine the adiabatic flame temperature for:

a. Complete combustion with 100 percent theoretical air,

b. Complete combustion with 400 percent theoretical air, and

c. Incomplete combustion (some CO in the products) with 90 percent theoretical air.



5. Adiabatic Flame Temperature

Cont…

Solution:

- The balanced equation for the combustion process with the theoretical amount of air is:

a. The combustion equation with 100 percent theoretical air

$$C_8H_{18}(l) + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 47N_2$$

- Energy balance for steady-flow system

$$\sum N_p\left(\bar{h}_f^o + \bar{h}(T) - \bar{h}^o\right)_p = \sum N_r\left(\bar{h}_f^o + \bar{h}(T) - \bar{h}^o\right)_r$$

5. Adiabatic Flame Temperature

Cont…

- The enthalpy of formation values for the reactants and products are summarized:

Substance	$\bar{h}_f^o$ (kJ/kmol)	$\bar{h}_{298K}$ (kJ/kmol)
$C_8H_{18}(l)$	-249,950	-
O_2	0	8682
N_2	0	8669
H_2O(g)	-241,820	9904
CO_2	-393,520	9364

- Substituting, we have

$$C_8H_{18}(l) + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 47N_2$$

$$\begin{aligned}
&(8kmol\ CO_2)[(-393{,}520 + \bar{h}_{CO_2} - 9364)\ kJ/kmol\ CO_2] \\
&+ (9kmol\ H_2O)[(-241{,}820 + \bar{h}_{H_2O} - 9904) kJ/kmol\ H_2O] \\
&+ (47kmol\ N_2)[(0 + \bar{h}_{N_2} - 8669)\ kJ/kmol\ N_2] \\
&= (1\ kmol\ C_8H_{18})(-249{,}950\ kJ/kmol\ C_8H_{18})
\end{aligned}$$

5. Adiabatic Flame Temperature

Cont…

- Which yields,

$$8\bar{h}_{CO_2} + 9\bar{h}_{H_2O} + 47\bar{h}_{N_2} = 5{,}646{,}081\ kJ$$

- By trial and error and interpolation, it is found to be $T_{Prod} = 2395\ K$

b. The balanced equation with complete combustion, 400 percent theoretical air

$$C_8H_{18}(l) + 50(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 188N_2$$

- Following same procedure used in (a), the AFT is determined to be $T_{Prod} = 962\ K$

  The temperature of the products decreases significantly as a result of using excess air.

5. Adiabatic Flame Temperature

Cont…

c. The balanced equation with incomplete combustion, 90 percent theoretical air is

$$C_8H_{18}(l) + 11.25(O_2 + 3.76N_2) \rightarrow 5.5CO_2 + 2.5CO + 9H_2O + 42.3N_2$$

Following same procedure used in (a), the AFT is determined to be $T_{Prod} = 2236\ K$

- In general,
  - ✓ The adiabatic flame temperature decreases as a result of incomplete combustion or using excess air.
  - ✓ The maximum adiabatic flame temperature is achieved when complete combustion occurs with the theoretical amount of air.

6. Heating Values of Fuels

- When a fuel undergoes combustion, its chemical energy is released mainly in the form of heat.
- The quantity of heat released per unit mass (or mole, or volume) of fuel is called the Heating Value or Calorific Value.
- Heating Value is the amount of heat released during the combustion of a specified amount of fuel is burned completely in a steady-flow process and the products are returned to the state of the reactants [4].
- Heating value equals to the absolute value of the enthalpy of combustion of the fuel.

$$Heating\ Value = |h_C|$$

6. Heating Values of Fuels

Cont…

- Heating value is a critical parameter in evaluating the energy content of fuels used in engines, power plants, and heating systems.
- Heating values are expressed as:
  - ✓ kJ/kg for solid and liquid fuels
  - ✓ kJ/m³ or kJ/kmol for gaseous fuels
- There are two types of heating values:

1. Higher Heating Value (HHV) - also known as Gross Calorific Value (GCV).

✓ Total energy released including latent heat of vaporization, i.e., when the H_2O in the products is in the liquid form.

Example: $C_nH_m + O_2 \rightarrow CO_2 + \frac{m}{2} H_2O\ (l) + \Delta H$

✓ Applicable in analyzing condensing boilers and theoretical limits.

6. Heating Values of Fuels

Cont…

2. Lower Heating Value (LHV) - also called Net Calorific Value (NCV).

- ✓ Energy released excluding latent heat, i.e., when the H_2O in the products is in the vapor form
- ✓ More relevant for practical engines and boilers, where exhaust gases leave at high temperature without condensing water.

- In general,
  - ✓ HHV > LHV because it includes condensation heat.
  - ✓ In practical systems (IC engines, gas turbines), LHV is commonly used.
  - ✓ In boiler and stationary systems where exhaust gases can condense, HHV may be used.

6. Heating Values of Fuels **Cont…**

- The relationship between HHV and LHV is defined by the latent heat of the water formed.

$$HHV = LHV + \left(N\bar{h}_{fg}\right)_{H_2O} (kJ/kg\ fuel)$$

Where: $\bar{h}_{fg}$ is the enthalpy of vaporization of water at the specified temperature.

7. Experimental Determination of Heating Values of Fuels

- Experimentally determining heating value is essential for evaluating fuel efficiency, designing combustion systems, and comparing energy sources.
- While theoretical values can be estimated from composition, experimental measurement provides accurate results.
- Laboratory calorimeters are the primary tools used to determine Higher Heating Value (HHV), and from it, the Lower Heating Value (LHV) can be obtained [6].
- All calorimeters operate on the First Law of Thermodynamics:

i.e., the heat released by the combustion reaction is transferred to a surrounding medium, causing a measurable temperature rise.

7. Experimental Determination of Heating Values of Fuels Cont…

Experimental Determination Methods

1. Bomb Calorimeter: The standard for solids & liquids

- The Bomb Calorimeter is the most common apparatus for precisely determining the Higher Heating Value (HHV) of solid and liquid fuels (e.g., coal, biomass, fuel oil, gasoline).

Key Components:

- ✓The bomb
- ✓Oxygen supply
- ✓Thermometer or temperature sensors
- ✓Water jacket
- ✓Ignition system

7. Experimental Determination of Heating Values of Fuels Cont…

2. Gas Calorimetry: Measures the heating value of gases

- Measures HHV by burning gas and capturing heat in a water-cooled chamber.

Key Components:

- ✓Continuous gas burner
- ✓Flow meter
- ✓Calorimeter chamber
- ✓Water flow and temperature sensors

7. Experimental Determination of Heating Values of Fuels Cont…

3. Combustion in Flow Calorimeter: for Liquid and gaseous fuels

- Measures: HHV or LHV
- A flow calorimeter is an apparatus where combustion occurs in a continuous flow of fuel and oxidizer, and the released heat is absorbed by a flowing stream of water.
- Unlike a bomb calorimeter, a standard flow calorimeter (like the Junkers) typically measures the Lower Heating Value (LHV) because the water vapor in the products does not fully condense.
- This method is the backbone of natural gas quality monitoring and energy billing in the gas industry.

Summary

- Thermodynamic properties are measured relative to a defined reference state, typically at 25°C and 1 atm, enabling consistent energy calculations.
- Reacting mixtures involve multiple species undergoing chemical change; their analysis requires tracking mole fractions, mass balance, and reaction stoichiometry.
- The enthalpy of formation quantifies the energy change when one mole of a compound forms from its elements in their reference states.
- Adiabatic flame temperature is the maximum temperature achieved during combustion without heat loss, influenced by fuel type, mixture ratio, and initial conditions.
- Fuels are characterized by their higher and lower heating values, indicating the energy released during complete combustion.

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Thank you !