13-2-1 [OJF] (a) Explain why the enthalpy of formation of CO_2 in MJ/kmol is the same as the heating value of carbon in MJ/kmol. (b) Express these quantities in the unit of MJ/kg.

SOLUTION

The heating value of a fuel is the amount of heat that is released when a unit mass (or mole) of a fuel is burned completely. For, carbon the complete combustion with oxygen produces carbon dioxide.

The enthalpy of combustion is given as:

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = \bar{h}_{f,CO_2}^o - \cancelto{0}{\bar{h}_{f,C}^o} - \cancelto{0}{\bar{h}_{f,O_2}^o} = \bar{h}_{f,CO_2}^o$$

$$\text{Therefore, Heating Value} = \left|\Delta\bar{h}_c^o\right| = \left|\bar{h}_{f,CO_2}^o\right|$$

13-2-2 [OJD] In a combustion chamber, propane (C_3H_8) is burned at a rate of 5 kg/h with air enters at a rate of 140 kg/h. Determine (a) the percent of excess air used, if the reactants enter at 25°C, also determine (b) the adiabatic flame temperature (T_{af}). Assume the products to be perfect gas mixture with c_p= 1.005 kJ/kg-K.

SOLUTION

Balance the theoretical reaction:

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2$$

(a) The percent of excess air:

$$5C_3H_8 + 140(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2 + dO_2$$

$$\frac{5}{44}C_3H_8 + \frac{140}{(4.76)29}(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2 + dO_2$$

$$0.113C_3H_8 + 1.015(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2 + dO_2$$

$$C_3H_8 + 8.98(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2 + dO_2$$

Balance the reaction:

$$C_3H_8 + 8.98(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 33.8N_2 + 3.98O_2$$

To get the percent excess air used:

$$\% \text{ excess} = \left(1\text{-}\frac{\overline{\text{AF}}}{\overline{\text{AF}}_{th}}\right)\times 100 = \left(1-\frac{8.98}{5}\right)\times 100 = 79.6\%$$

(b) The adiabatic flame temperature is:

$$T_{\text{f,ad}} = T_i + \frac{(-\Delta h_C)}{(1+\text{AF})c_p}$$

$$\text{AF} = \frac{8.98(4.76)(29)}{44} = 28\,\frac{\text{kg of air}}{\text{kg of fuel}}$$

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = 3\bar{h}_{f,CO_2}^o + 4\bar{h}_{f,H_2O}^o - \bar{h}_{f,C_3H_8}^o$$
$$\Delta\bar{h}_c^o = 3(-393520) + 4(-241820) - (-103850)$$
$$\Delta\bar{h}_c^o = -2043990 \text{ kJ/kmol}$$

$$\Rightarrow \Delta h_c^o = \frac{\Delta\bar{h}_c^o}{\bar{M}_F} = \frac{-2043990}{44} = -46454.32 \text{ kJ/kg}$$

$$T_{f,ad} = 298 + \frac{46454.32}{(1+28)1.005} = 1891.9 \text{ K}$$

TEST Verification: Use the n-PG non-premixed combustion TESTcalc to verify the results.

13-2-3 [OJM] Calculate the higher heating value (HHV) of methane (CH_4) per unit mass of fuel at (a) 298 K, and (b) 500 K.

SOLUTION

Balance the theoretical reaction:

$$CH_4 + 2\left(O_2 + 3.76N_2\right) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

(a) HHV at 298 K:

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = -877305.53 - (-74913.17) = -\ 802392.36\,\text{kJ/kmol}$$

$$\Rightarrow \Delta h_c^o = \frac{\Delta\bar{h}_c^o}{\bar{M}_F} = \frac{-\ 802392.36}{16} = -\ 50149.525\,\text{kJ/kg}$$

LHV = 50149.525 kJ/kg

$$\text{HHV} = \text{LHV} + \nu_{H_2O} h_{fg,H_2O} \Rightarrow \text{HHV} = 50149.525 + 4884.6$$

$$\Rightarrow \text{HHV} = 55034.13\ \text{kJ/kg}$$

(b) HHV at 500K:

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = -812248.03 - (-11791.5) = -\ 800456.53\,\text{kJ/kmol}$$

$$\Rightarrow \Delta h_c^o = \frac{\Delta\bar{h}_c^o}{\bar{M}_F} = \frac{-\ 800456.53}{16} = -50028.53\,\text{kJ/kg}$$

$$\text{HHV} = \text{LHV} + \nu_{H_2O} h_{fg,H_2O} \Rightarrow \text{HHV} = 50028.53 + 3656.14$$

$$\Rightarrow \text{HHV} = 53684.67\ \text{kJ/kg}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-4 [BVQ] Calculate the enthalpy of combustion of propane (C_3H_8) at 25^{o}C on a mass basis.

SOLUTION

Balance the theoretical reaction:

$$C_3H_8 + 5\left(O_2 + 3.76N_2\right) \rightarrow 3CO_2 + 4H_2O + 18.8N_2$$

The enthalpy of combustion is;

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = -2147872.715 - (-104199.96) = -2043672.74 \text{ kJ/kmol}$$

$$\Rightarrow \Delta h_c^o = \frac{\Delta\bar{h}_c^o}{\bar{M}_F} = \frac{-2043672.74}{44} = -46447.11 \text{ kJ/kg} = -46.447 \text{ MJ/kg}$$

TEST Verification: Use the n-PG non-premixed combustion TESTcalc to verify the results.

13-2-5 [OJW] In an adiabatic combustion chamber, methane (CH_4) is burned at a rate of 1 kg/s with 1 kg/s of oxygen with both the fuel and oxidizer entering the chamber separately at 100 kPa and 300 K. Determine (a) the temperature of the products and (b) the rate of entropy generation ($\dot{S}_{gen}$).

SOLUTION

The balanced reaction is:

$$\mathrm{CH_4} + 0.5\mathrm{O_2} \rightarrow 0.75\mathrm{CH_4} + 0.25\mathrm{CO_2} + 0.5\mathrm{H_2O}$$

(a) Since $\dot{Q}$ and W_{ext} are 0;

$$\sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r = 0$$

$$\bar{h}_P - \bar{h}_R = 0$$

$$\sum_p \nu_p \bar{h}^\circ_{f,p} - \sum_r \nu_r \bar{h}^\circ_{f,r} + \sum_p \nu_p \bar{h}_p^{\mathrm{IG}} - \sum_r \nu_r \bar{h}_r^{\mathrm{IG}} = 0$$

$$\bar{h}_P(T_0) - \bar{h}_R(T_0) + \sum_p \nu_p \bar{h}_p^{\mathrm{IG}} - \sum_r \nu_r \bar{h}_r^{\mathrm{IG}} = 0$$

T_{af} is the maximum temperature that can be obtained for a given inlet temperature T_i.

$$\bar{h}_R = -74788 \text{ kJ/kmol}$$

$\bar{h}_P$ depends on T_{af} which can be calculated using iterative solutions until $\bar{h}_P = \bar{h}_R$

$$T_{af} = 2427.9 \text{ K}$$

(b) $\bar{S}_{gen} = \bar{S}_P - \bar{S}_R = \sum \nu_p \bar{s}_P - \sum \nu_r \bar{s}_R$

$$\bar{S}_{gen} = \bar{S}_P - \bar{S}_R = 473.93 - 289.24 = 184.68 \text{ kJ/kmol}\cdot\text{K}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-6 [OJJ] Hydrogen (H_2) at 10^{o}C is burned with 30% excess air that is also at 10^{o}C during an adiabatic steady flow combustion process. Assuming complete combustion, (a) determine the exit temperature of the product gases using the PG mixture model with a uniform value of c_p= 1.005 kJ/kg-K. (b) What-if Scenario: What would the exit temperature be if the IG mixture model were used?

SOLUTION

The theoretical reaction is:

$$\mathrm{H_2} + a\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow b\mathrm{H_2O} + c\mathrm{N_2}$$

The balanced theoretical reaction is:

$$\mathrm{H_2} + 0.5\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow \mathrm{H_2O} + 1.88\mathrm{N_2}$$

For 30% excess air, the amount of air should be increased by a factor of 1.3 compared to the theoretical amount. Thus the actual reaction can be set up as follows;

$$\mathrm{H_2} + 0.65\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow \mathrm{H_2O} + 2.44\mathrm{N_2} + 0.15\mathrm{O_2}$$

The mass-based air-fuel ratio now can be obtained from the above equation as

$$\mathrm{AF} = \overline{\mathrm{AF}}\left(\frac{\bar{M}_{\mathrm{Air}}}{\bar{M}_{\mathrm{F}}}\right) = (0.65)\times(4.76)\times\frac{(29)}{(2)} = 44.86\ \frac{\text{kg of air}}{\text{kg of fuel}}$$

$$\Delta\bar{h}_C^{\mathrm{o}} = \sum_p \nu_p \bar{h}_{f,p}^{\mathrm{o}} - \sum_r \nu_r \bar{h}_{f,r}^{\mathrm{o}}$$

$$\begin{aligned}\Delta\bar{h}_C^{\mathrm{o}} &= (\bar{h}_{f,\mathrm{H_2}O}^{\mathrm{o}} + 2.44\bar{h}_{f,N_2}^{\mathrm{o}} + 0.15\bar{h}_{f,O_2}^{\mathrm{o}}) - (\bar{h}_{f,\mathrm{H_2}}^{\mathrm{o}}) \\ &= -241820\ \text{kJ/kmol}\end{aligned}$$

$$\text{Therefore, } \Delta h_C^{\mathrm{o}} = \left(\frac{\Delta\bar{h}_C^{\mathrm{o}}}{\bar{M}_{\mathrm{H_2}}}\right) = \frac{-241820}{2} = -120910\ \text{kJ/kg}$$

Therefore the adiabatic flame temperature or the exit temperature can be obtained from the equation as follows:

$$T_{\mathrm{af}}^{\mathrm{PG}} = T_i + \frac{(-\Delta h_C)}{c_p\,(1+\mathrm{AF})} = 10 + \frac{120910}{(1.005)(1+44.86)} = 2646.5^{\mathrm{o}}\mathrm{C} = 2919.5\ \mathrm{K}$$

TEST Verification: Use the n-PG non-premixed combustion TESTcalc to verify the results.

13-2-7 [OWB] Methane gas at 350 K and 1 atm enters a combustion chamber, where it is mixed with air entering at 550 K and 1 atm. The products of combustion exit at 1500 K and 1 atm with the product analysis given. For an operation at steady state, neglecting KE and PE, determine (a) the rate of heat transfer from the combustion chamber in kJ per kmol of fuel. Use the IG mixture model. (b) What-if Scenario: What would the rate of heat transfer be if the PG mixture model were used?

SOLUTION Balance the theoretical reaction:

$$\mathrm{CH_4} + c\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow a\mathrm{CO_2} + b\mathrm{O_2} + c\mathrm{N_2}$$

Balancing the equation;

$$\mathrm{CH_4} + 2\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O} + 7.5\mathrm{N_2}$$

(a) The heat transfer from the combustion chamber is calculated;

$$\frac{\dot{Q}}{\dot{\eta}_f} = \sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r + \frac{W_{ext}}{\dot{\eta}_f} = \bar{h}_P - \bar{h}_R$$

$$\bar{h}_R = \dot{\eta}_f \sum_r \nu_r \bar{h}_r = -1796.28 \ \mathrm{kJ/kmol}$$

$$\bar{h}_P = \dot{\eta}_f \sum_p \nu_p \bar{h}_p = -430858.9 \ \mathrm{kJ/kmol}$$

$$\dot{Q} = -429062.62 \ \mathrm{kJ/kmol}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-8 [OWR] Diesel fuel is burned with 25% excess air in a steady-state combustor. Both fuel and air enters at 77°F the products leave at 800°R. Assuming complete combustion, determine (a) the mass flow rate necessary to supply a heating rate of 2000 Btu/s, (b) the change in entropy (*ΔS*) per lbm of fuel. Assume the pressure remains constant at 14.7 psia.

SOLUTION

The theoretical balanced reaction is:

$$C_{12}H_{26} + 18.5(O_2 + 3.76\,N_2) \rightarrow +12CO_2 + 13H_2O + 69.56O_2$$

With 25% excess air:

$$C_{12}H_{26} + 23.125(O_2 + 3.76\,N_2) \rightarrow +12\,CO_2 + 13\,H_2O + 4.625\,O_2 + 86.994N_2$$

(b) The heat transfer from the combustion chamber is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$

$$-Q_{out} = \sum \eta_P \left(\overline{h_f^\circ} + \bar{h} - \bar{h}^\circ\right)_P - \sum \eta_R \left(\overline{h_f^\circ} + \bar{h} - \bar{h}^\circ\right)_R = \sum \eta_P \left(\overline{h_f^\circ} + \bar{h} - \bar{h}^\circ\right)_P - \sum \eta_R \overline{h_f^\circ}_{,R}$$

$$\begin{aligned}
-Q_{out} &= (12)(-169,300 + 6552.9 - 4027.5) + (13)(-104,040 + 6396.9 - 4258.0) \\
&+ (4.625)(0 + 5602.0 - 3725.1) + (86.856)(0 + 5564.4 - 3729.5) - (1)(-125,190) - (0) - (0) \\
&= (-2,001,295.2) + (-1,324,714.3) + (8680.66) + (159,372.07) + (125,190) \\
-Q_{out} &= -3,032,766.77 \text{ Btu/lbmol } C_{12}H_{16}
\end{aligned}$$

Then the required mass flow rate for the fuel heat transfer of 2000 Btu/s is,

$$\dot{m} = \dot{N}\bar{M} = \left(\frac{\dot{Q}}{Q}\right)\bar{M} = \left(\frac{2000}{3032766.77}\right)(170) = 0.112 \text{ lbm/s}$$

(b) Change in entropy per lbm of fuel is,

$$\Delta S = \frac{2000}{537} = 3.72 \text{ Btu/R}$$

TEST Verification: Use the n-PG non-premixed combustion TESTcalc to verify the results.

13-2-9 [OWO] Gasoline enters a combustion chamber at 1 atm, 298 K at a rate of 0.09 kg/min where it burns steadily and completely with 70% excess air that enters the chamber at 1 atm, 200 K. If the exit temperature of the combustion products is 800 K, determine (a) the mass flow rate of air and (b) the rate of heat transfer. Use the IG mixture model for gases. Represent gasoline by liquid octane. (c) What-if Scenario: What would the rate of heat transfer be if the excess air were used only 20%?

SOLUTION

The balanced theoretical reaction:

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

Actual Reaction with 170% Theoretical Air:

$$C_8H_{18}(l) + (1.7)(12.5)\left(O_2 + 3.76N_2\right) \rightarrow bCO_2 + cH_2O + aN_2 + bO_2$$

$$\text{N: } 2(12.5)(1.7)(3.76) = 2a \Rightarrow a = 79.9$$
$$\text{O: } 2(1.7)(12.5) = 16 + 9 + 2b \Rightarrow b = 8.75$$

$$C_8H_{18}(l) + 21.25\left(O_2 + 3.76N_2\right) \rightarrow 8CO_2 + 9H_2O + 79.9N_2 + 8.75O_2$$

$$\text{AF} = \overline{\text{AF}}\left(\frac{\bar{M}_{air}}{\bar{M}_F}\right) = (21.25)(4.76)\frac{29}{(8)(12)+(18)(1)} = 25.73\frac{\text{kg of air}}{\text{kg of fuel}}$$

$$\dot{m}_{air} = (\dot{m}_F)\text{AF} = (0.09)(25.73) = 2.31\frac{\text{kg of air}}{\text{min}}$$

$$\frac{\dot{Q}}{\dot{n}_f} = \sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r + \frac{\dot{W}_{ext}}{\dot{n}_f} = \bar{h}_P - \bar{h}_R$$

$$\bar{h}_R = \sum_r \nu_r \bar{h}_r = -539129 \text{ kJ/kmol}$$

$$\bar{h}_P = \sum_p \nu_p \bar{h}_p = -3639343 \text{ kJ/kmol}$$

$$\dot{n}_f = \frac{\dot{m}_f}{\bar{M}_F} = \frac{0.09}{(60)(114)} = 1.31\times10^{-5} \text{ kmol/s}$$

$$\dot{Q} = (1.31\times10^{-5})(-3639343 - (-539129)) = -40.61 \text{ kW}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-10 [BVF] Gaseous ethane (C_2H_6) and 300% excess oxygen at 25°C, 100 kPa react in a steady-flow reaction chamber. The products exits at 3000 K. Determine the amount of heat transfer (q) per kg of ethane.

SOLUTION

The balanced theoretical reaction is:

$$\mathrm{C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O}$$

With 300% excess air:

$$\mathrm{C_2H_6 + 4(3.5)O_2 \rightarrow 2CO_2 + 3H_2O + 10.5O_2}$$

$$\frac{\dot{Q}}{\dot{\eta}_f} = \sum_p \nu_p \overline{h}_p - \sum_r \nu_r \overline{h}_r + \frac{W_{ext}}{\dot{\eta}_f} = \overline{h}_P - \overline{h}_R$$
$$\overline{h}_R = \dot{\eta}_f \sum_r \nu_r \overline{h}_r = -84129.57 \text{ kJ/kmol}$$
$$\overline{h}_P = \dot{\eta}_f \sum_p \nu_p \overline{h}_p = 202521.62 \text{ kJ/kmol}$$

$$Q = 286651.2 \text{ kJ/kmol}$$
$$\dot{Q} = \frac{286651.2}{30} = 9555 \text{ kJ/kg}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-11 [OWS] Determine the adiabatic flame temperature (T_{af}) for octane (C_8H_{18}) burning with 20% excess air. The inlet conditions are 100 kPa, and 298 K. Use the IG model.

SOLUTION

The balanced theoretical reaction:

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

Actual Reaction with 120% Theoretical Air:

$$\mathrm{C_8H_{18}(l) + (1.2)(12.5)\left(O_2 + 3.76N_2\right) \rightarrow \mathit{a}CO_2 + \mathit{b}H_2O + cN_2 + \mathit{d}O_2}$$

$$\mathrm{C_8H_{18}(l) + 15\left(O_2 + 3.76N_2\right) \rightarrow 8CO_2 + 9H_2O + 56.4N_2 + 2.5O_2}$$

$$\mathrm{AF} = \overline{\mathrm{AF}}\left(\frac{\bar{M}_{air}}{\bar{M}_F}\right) = (15)(4.76)\frac{29}{(114.23)(1)} = 18.12\,\frac{\text{kg of air}}{\text{kg of fuel}}$$

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = -5325628.94 - (-208752.83) = -5116876.1 \;\; \text{kJ/kmol}$$

$$\Rightarrow \Delta h_c^o = \frac{\Delta\bar{h}_c^o}{\bar{M}_F} = \frac{-5116876.1}{114.23} = -44794.5 \;\; \text{kJ/kg}$$

For IG Model adiabatic flame temperature is calculated;

$$\frac{\dot{Q}}{\dot{\eta}_f} = \sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r + \frac{W_{ext}}{\dot{\eta}_f}$$

Since $\dot{Q}$ and W_{ext} are 0;

$$\sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r = 0$$

$$\bar{h}_P - \bar{h}_R = 0$$

$$\sum_p \nu_p \bar{h}^\circ{}_{f,p} - \sum_r \nu_r \bar{h}^\circ{}_{f,r} + \sum_p \nu_p \bar{h}_p^{IG} - \sum_r \nu_r \bar{h}_r^{IG} = 0$$

$$\bar{h}_P(T_0) - \bar{h}_R(T_0) + \sum_p \nu_p \bar{h}_p^{IG} - \sum_r \nu_r \bar{h}_r^{IG} = 0$$

T_{af} is the maximum temperature that can be obtained for a given inlet temperature T_i.

$\bar{h}_R = -208752.83 \text{ kJ/kmol}$

$\bar{h}_P$ depends on T_{af} which can be calculated using iterative solutions until $\bar{h}_P = \bar{h}_R$

$T_{af} = 2137.3 \text{ K}$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-12 [OWA] Benzene gas (C_6H_6) at 25°C is burned during a steady flow combustion process with 90% theoretical air that enters the combustion chamber at 25°C. All the hydrogen in the fuel burns to H_2O, but part of the carbon burns to CO. If the products leave at 1500 K, determine (a) the mole fraction of the CO in the products (in percent) and (b) the heat transfer ($\bar{q}$) from the combustion chamber during this process per unit mole of fuel.

SOLUTION

(a) The mole fraction of CO in the products:

The balanced theoretical reaction is:

$$C_6H_6 + 7.5(O_2 + 3.76\,N_2) \rightarrow +\ 6\,CO_2 + 3H_2O + 28.2\,N_2$$

The balanced actual reaction with 90% theoretical air is:

$$C_6H_6 + 6.75(O_2 + 3.76\,N_2) \rightarrow +\ 4.5\,CO_2 + 1.5\,CO + 3H_2O + 25.38\,N_2$$

The mole fraction of CO in the products is:

$$y_{CO} = \left(\frac{N_{CO}}{N_{Total}}\right) = \left(\frac{1.5}{4.5 + 1.5 + 3 + 25.38}\right) = 0.043 \text{ or } 4.3\ \%$$

(b) The heat transfer from the combustion chamber is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$

$$\dot{Q} = \sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r + \frac{\cancel{\dot{W}_{ext}}^{\,0}}{\dot{n}_F} = \bar{h}_P - \bar{h}_R$$

$$\dot{Q} = \bar{h}_P - \bar{h}_R = -1207308.7 - 82959$$

$$\dot{Q} = -1290267.74\ \text{kJ/kmol}\ C_6H_6$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-13 [OWH] Methane (CH_4) enters a furnace at 100 kPa and 300 K. It is burned with 25% excess air that also enters at 300 K and 100 kPa. Assuming the exhaust temperature to be 500 K and the heat transfer load to be 20 kW, determine (a) fuel consumption rate in kg/h. (b) What-if Scenario: What would the fuel consumption rate be if theoretical amount of air were used? Assume complete combustion and the IG model for gas mixtures.

SOLUTION

The balanced reaction equation for complete combustion is,

$$\mathrm{CH_4}(g) + 11.9\,\mathrm{O_2} \to +\ \mathrm{CO_2} + 2\,\mathrm{H_2O} + 9.4\mathrm{N_2} + 0.5\,\mathrm{O_2}$$

(a) Conservation of Energy:

$$\frac{\dot{Q}\overline{M}_F}{\dot{m}_F} = \sum_p \nu_p \bar{h}_p - \sum_r \nu_p \bar{h}_p$$

Therefore,

$$\frac{\dot{Q}\overline{M}_F}{\dot{m}_F} = -796249.58 - (-74158.63) = -722090.94\ \mathrm{kJ/kmol}$$

The fuel consumption rate can be calculated by,

$$\dot{m}_F = \frac{(-20)(16.04)(3600)}{-722090.94} = 1.6\ \mathrm{kg/s}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-14 [OWL] Methane (CH_4) enters a steady flow adiabatic combustion chamber at 100 kPa and 25°C. It is burned with 100% excess air that also enters at 25°C and 100 kPa. Assuming complete combustion, determine (a) the temperature (T) of the products, (b) the entropy generation ($\overline{S}_{gen}$) and (c) the reversible work. Assume that T_0 = 298 K and the products leave the combustion chamber at 100 kPa.

SOLUTION

The balanced reaction equation for complete combustion with 100% excess is as follows:

$$CH_4 + 4\,(O_2 + 3.76\,N_2) \rightarrow CO_2 + 2\,H_2O + O_2 + 15.04\,N_2$$

(a) For adiabatic flame temperature $\overline{h}_P = \overline{h}_R$;

$$\sum_p \nu_p \overline{h}_p - \sum_r \nu_r \overline{h}_r = 0$$

$$\sum_p \nu_p \overline{h}^\circ{}_{f,p} - \sum_r \nu_r \overline{h}^\circ{}_{f,r} + \sum_p \nu_p \overline{h}_p^{IG} - \sum_r \nu_r \overline{h}_r^{IG} = 0$$

$$\overline{h}_P(T_0) - \overline{h}_R(T_0) + \sum_p \nu_p \overline{h}_p^{IG} - \sum_r \nu_r \overline{h}_r^{IG} = 0$$

$$\overline{h}_R = -74949.65\,\text{kJ/kmol}$$

$\overline{h}_P$ depends on T_{af} which can be calculated guessing until $\overline{h}_P = \overline{h}_R$

$T_{af} = 1481.83$ K

b) Entropy generation:

$$\overline{S}_{gen} = \overline{S}_P - \overline{S}_R = \sum \nu_p \overline{s}_P - \sum \nu_r \overline{s}_R$$

$$\overline{S}_{gen} = \overline{S}_P - \overline{S}_R = 5079.66 - 3985.9 = 1093.7\,\text{kJ/kmol}\cdot\text{K}$$

c) Irreversibility:

$$X_{destroyed} = T_o \overline{S}_{gen} = (298)(1093.7) = 325939.28\,\text{kJ/kmol}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-15 [OWI] Liquid octane (C_8H_{18}) enters the combustion chamber of a gas turbine steadily at 100 kPa, 25°C, and it is burned with air that enters the combustion chamber at the same state. Disregarding any changes in KE and PE, determine the adiabatic flame temperature (T_{af}) for (a) complete combustion with 100% theoretical air and (b) complete combustion with 200% theoretical air. (c) What-if Scenario: What would the answer in part (a) be for incomplete combustion where some CO were produced with 80% theoretical air?

SOLUTION

The balanced theoretical reaction:

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

(a) For IG Model adiabatic flame temperature is calculated;

$$(8\,\text{kmol CO}_2)[-393520 + \bar{h}_{CO2} - 9364)\,\text{kJ}/\text{kmol CO}_2\,] +$$
$$+(9\,\text{kmol H}_2\text{O})[-241.820 + \bar{h}_{H_2O} - 9904)\,\text{kJ}/\text{kmol H}_2\text{O} + (47\,\text{kmol N}_2)[0 + \bar{h}_{N_2} - 8669)\,\text{kJ}/\text{kmol N}_2 +$$
$$+(1\,\text{kmol C}_8\text{H}_{18})(-24950\,\text{kJ}/\text{kmol C}_8\text{O}_{18})$$

$$8\bar{h}_{CO_2} + 9\bar{h}_{H_2O} + 47\bar{h}_{N_2} = 5646081\,\text{kJ}$$

Interpolate temperatures for corresponding enthalpy,

Enthalpy: $5646081\,kJ\,/\,(\text{no. of moles}) = 5646081/(8+9+47) = 88220$

$T_{af} = 2395\text{ K}$

(b) Balanced equation for complete combustion with 200% theoretical air is,

$$C_8H_{18} + 25\,(O_2 + 3.76\,N_2) \rightarrow +\,8\,CO_2 + 9\,H_2O + 12.5\,O_2 + 94\,N_2$$

$$(8\,\text{kmol CO}_2)[-393520 + \bar{h}_{CO2} - 9364)\,\text{kJ}/\text{kmol CO}_2\,] +$$
$$+(9\,\text{kmol H}_2\text{O})[-241820 + \bar{h}_{H_2O} - 9904)\,\text{kJ}/\text{kmol H}_2\text{O} + (12.5\,\text{kmol O}_2)[0 + \bar{h}_{O_2} - 8682)\,\text{kJ}/\text{kmol O}_2\,]$$
$$+(94\,\text{kmol N}_2)[0 + \bar{h}_{N_2} - 8669)\,\text{kJ}/\text{kmol N}_2 = (1\,\text{kmol C}_8\text{H}_{18})(-249950\,\text{kJ}/\text{kmol C}_8\text{O}_{18}$$

$$8\bar{h}_{CO_2} + 9\bar{h}_{H_2O} + 12.5\bar{h}o_2 + 94\bar{h}_{N_2} = 6162049\text{ kJ}$$

(b)Repeat interpolation from part (a) Resulting Adiabatic flame temperature is

$T_{af} = 1506\text{ K}$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-16 [OWN] Methane gas at 450 K and 100 kPa enters a combustion chamber, where it burns steady and completely with theoretical amount of air entering at 500 K and 100 kPa. The products of combustion gas exit at 1900 K and 100 kPa. For operation at steady state, neglecting the KE and PE, determine (a) the rate of heat transfer from the combustion chamber in kJ per kmol of fuel.

SOLUTION

The balanced theoretical reaction is:

$$\mathrm{CH_4} + 2\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O} + 7.52\mathrm{N_2}$$

The rate of heat transfer can be expressed as:

$$\frac{\dot{Q}}{\dot{n}_F} = \sum_p \nu_p \overline{h}_p - \sum_r \nu_r \overline{h}_r + \frac{\cancel{W_{\text{ext}}}^{\,0}}{n_F} = \overline{h}_P - \overline{h}_R$$

$$\dot{Q} = \frac{-262108.43 - (-12114.6)}{114}$$

$$\dot{Q} = -249993.837 \;\; \mathrm{kJ/kmol}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-17 [OWE] Ethene (C_2H_4) at 25°C and 1 atm is burned with 300% excess air at 25°C and 1 atm. Assuming that this reaction takes place reversibly at 25°C and that the products leave at 25°C and 1 atm. (a) Determine the reversible work (w_{rev}) for this process per kg of fuel. Use the IG mixture model. (b) What-if Scenario: What would the reversible work be if the PG mixture model were used?

SOLUTION

The balanced theoretical reaction is:

$$C_2H_4 + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 11.28N_2$$

300% excess air:

$$C_2H_4 + 12(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 45.12N_2 + 9O_2$$

(a) The reversible work is:

$$\overline{S}_{gen} = \overline{S}_P - \overline{S}_R = 4444.37 \text{ kJ/kmol}\cdot\text{K}$$

$$\dot{S}_{gen} = \frac{\overline{S}_{gen}}{\overline{M}} = \frac{4444.37}{28} = 158.72 \text{ kJ/kg}\cdot\text{K}$$

$$\dot{W}_{rev} = T_0\dot{S}_{gen}$$

$$\dot{W}_{rev} = 298(158.72)$$

$$\dot{W}_{rev} = 47298.56 \text{ kJ/kg}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-18 [OWK] Consider the same combustion process as in above problem *13-2-17 [OWE], but let it takes place adiabatically. Assume that each constituent in the product is at 1 atm and at the adiabatic flame temperature (T_{af}). The temperature of the surrounding is 25^{o}C. Determine the irreversibility of the adiabatic combustion process per kg of fuel.

SOLUTION

The balanced reaction is:

$$C_2H_4 + 12(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 45.12N_2 + 9O_2$$

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = -1271611.6 - (52241.12) = -1323852.72$$

$$\Rightarrow \Delta h_c^o = \frac{\Delta\bar{h}_c^o}{\bar{M}_F} = \frac{-1323852.72}{28} = -47280.45 \,\text{kJ/kg}$$

$$T_{f,ad} = T_i + \frac{(-\Delta h_C)}{(1+AF)c_p}$$

$$AF = \frac{12(4.76)(29)}{28} = 59.16 \frac{\text{kg of air}}{\text{kg of fuel}}$$

$$T_{f,ad} = 1013.6 \text{ K}$$

$$\bar{S}_{gen} = \bar{S}_P - \bar{S}_R = 13881.8 - 11618.13 = 2263.74 \frac{\text{kJ}}{\text{kmol}\cdot\text{K}}$$

$$\dot{S}_{gen} = \frac{\bar{S}}{\bar{M}} = \frac{2263.74}{28} = 80.847 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$\dot{W}_{rev} = T_o \dot{S}_{gen} = 298(80.847) = 24092.4 \frac{\text{kJ}}{\text{kg}}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-19 [OWG] Ethylene (C_2H_4) at 25°C and 1 atm is burned with 300% excess air at 25°C and 1 atm. Assuming that this reaction takes place adiabatically at 25°C and that the products leave at 25°C and 1 atm. Determine the irreversibility of the process per kg of fuel. Use the PG mixture model. Assume c_p to be uniform at 1.005 kg/kJ K.

SOLUTION

The balanced theoretical reaction is:

$$C_2H_4 + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 11.28N_2$$

With 300% excess air:

$$C_2H_4 + 12(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 45.12N_2 + 9O_2$$

$$T_{f,ad} = T_i + \frac{(-\Delta h_C)}{(1+AF)c_p}$$

$$\Delta\bar{h}_c^o = \sum \nu_p \bar{h}_{f,p}^o - \sum \nu_r \bar{h}_{f,r}^o = -1270953.41 - (-52211.33) = -1323164.74 \text{ kJ/kmol}$$

$$\Rightarrow \Delta h_c^o = \frac{\Delta\bar{h}_c^o}{\bar{M}_F} = \frac{-1323164.73}{28} = -47255.88 \text{ kJ/kg}$$

$$AF = \frac{12(4.76)(29)}{28} = 59.16 \frac{\text{kg of air}}{\text{kg of fuel}}$$

$$T_{f,ad} = 298 + \frac{(47255.88)}{(1+59.16)1.005} = 1080 \text{ K}$$

$$\bar{S}_{gen} = \bar{S}_P - \bar{S}_R = \sum \nu_p \bar{s}_p - \sum \nu_r \bar{s}_r$$

$$\bar{S}_{gen} = 13846.01 - 11618.11 = 2227.9 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}}$$

$$\dot{S}_{gen} = \frac{\bar{S}_{gen}}{\bar{M}} = \frac{2227.9}{28} = 79.56 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$\dot{W}_{irrversible} = T_0 \dot{S}_{gen}$$

$$\dot{W}_{irrversible} = 298\,(79.56) = 23708.88 \frac{\text{kJ}}{\text{kg}}$$

TEST Verification: Use the n-PG non-premixed combustion TESTcalc to verify the results.

13-2-20 [OWC] Liquid propane (C_3H_8) enters a combustion chamber at 25°C, 100 kPa at a rate of 0.5 kg/min where it is mixed and burned with 150% theoretical air which enters at 10°C. Only 90% of C is converted to CO_2, the rest to CO while the hydrogen burns completely into H_2O. The products leave at 1000 K and 100 kPa. Determine (a) the mass flow rate of air, (b) the rate of heat transfer and (c) the rate of entropy generation assuming the surroundings to be at 300 K.

SOLUTION

The balanced theoretical reaction is:

$$\mathrm{C_3H_{8(\mathit{l})}} + 5\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow 3\mathrm{CO_2} + 4\mathrm{H_2O} + 18.8\mathrm{N_2}$$

The reaction for 150% theoretical air and 90% C is:

$$\mathrm{C_3H_{8(\mathit{l})}} + 7.5\left(O_2 + 3.76N_2\right) \rightarrow 2.7\mathrm{CO_2} + 4\mathrm{H_2O} + 28.2\mathrm{N_2} + 2.8\mathrm{O_2} + 0.3\mathrm{CO}$$

The mass-based air-fuel ratio now can be obtained from above equation as

$$\mathrm{AF} = \overline{\mathrm{AF}}\left(\frac{\bar{M}_{\mathrm{Air}}}{\bar{M}_{\mathrm{F}}}\right)$$

$$\Rightarrow (7.5)\times(4.76)\times\left(\frac{29}{3\times 12 + 8\times 1}\right)$$

$$\Rightarrow 23.53\ \frac{\text{kg of air}}{\text{kg of fuel}}$$

(a) The mass flow rate of air, therefore, is

$$\dot{m}_{\mathrm{Air}} = \left(\dot{m}_F\right)\left(\mathrm{AF}\right) = \frac{(0.5)(23.53)}{(60)} = 0.196\ \frac{\text{kg of air}}{\text{sec}}$$

(b) From energy equation, the rate of heat transfer can be expressed as

$$\frac{\dot{Q}}{\dot{n}_F} = \sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r + \frac{\cancel{\dot{W}_{\mathrm{ext}}}^{0}}{\dot{n}_F} = \bar{h}_P - \bar{h}_R;$$

Therefore, the heat transfer rate in kW can be obtained from above energy equation as

$$\dot{Q} = -225.67 - (26.19) = -200\ \mathrm{kW}$$

(c) From entropy equation:

$$\dot{S}_{\mathrm{gen}} = \dot{n}_F\left[\sum_p \nu_p \bar{s}_p - \sum_r \nu_r \bar{s}_r\right] - \frac{\dot{Q}}{T_B} = \dot{n}_F\left[\bar{s}_P - \bar{s}_R\right] - \frac{\dot{Q}}{T_B};$$

Therefore,

$$\dot{S}_{\text{gen}} = \left[\dot{S}_P - \dot{S}_R\right] - \dot{Q}/T_B$$

$$= [1.71 - 1.37] - \frac{(-200)}{300}$$

$$= 1\ \text{kW/K}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-21 [OWZ] Liquid octane enters an internal combustion engine operating at steady state with a mass flow rate of 0.0018 kg/s and is mixed with the theoretical amount of air. The fuel and air enter the engine at 25°C, 100 kPa. The mixture burns completely and the products leave the engine at 600°C. The engine develops a power output of 30 horsepower. Neglecting KE and PE, determine (a) the rate of heat transfer from the engine. (b) What-if Scenario: What would the rate of heat transfer be if PG model were used?

SOLUTION

The balanced equation for combustion with theoretical air is:

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

$$\dot{Q} = \sum_p \eta_p h_p - \sum_r \eta_r h_r + \dot{W}_{ext} = h_P - h_R + \dot{W}_{ext}$$

$$\dot{Q} = -64.64 - (-3.93) + 22.37$$

$$\dot{Q} = -38.33 \text{ kW}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-22 [OWP] Octane (C_8H_{18}) at 24^{o}C and 100 kPa enters well insulated reactor and reacts at the same temperature and pressure. For steady state operation and negligible effects of KE and PE, determine the temperature of the combustion products for the complete combustion with (a) theoretical amount of air and (b) 300% theoretical air.

SOLUTION

(a) The balanced equation for combustion with theoretical air is,

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

When calculating adiabatic flame temperature;

$$\bar{h}_P - \bar{h}_R = 0$$

$$\sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r = 0$$

$$\sum_p \nu_p \bar{h}^\circ_{f,p} - \sum_r \nu_r \bar{h}^\circ_{f,r} + \sum_p \nu_p \bar{h}_p^{IG} - \sum_r \nu_r \bar{h}_r^{IG} = 0$$

$$\bar{h}_P(T_0) - \bar{h}_R(T_0) + \sum_p \nu_p \bar{h}_p^{IG} - \sum_r \nu_r \bar{h}_r^{IG} = 0 \Rightarrow \bar{h}_C = \bar{h}_P(T_0) - \bar{h}_R(T_0)$$

$$\bar{h}_R = -210633.38 \text{ kJ/kmol}$$

$\bar{h}_P$ depends on T_{af} which can be calculated guessing until $\bar{h}_P = \bar{h}_R$

$T_{af} = 2410.8$ K

(b) With 300% theoretical air:

$$C_8H_{18} + 37.5(O_2 + 3.76\,N_2) \rightarrow 8CO_2 + 9\,H_2O + 141N_2 + 25O_2$$

$$\bar{h}_P - \bar{h}_R = 0$$

$$\sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r = 0$$

$$\sum_p \nu_p \bar{h}^\circ_{f,p} - \sum_r \nu_r \bar{h}^\circ_{f,r} + \sum_p \nu_p \bar{h}_p^{IG} - \sum_r \nu_r \bar{h}_r^{IG} = 0$$

$$\bar{h}_P(T_0) - \bar{h}_R(T_0) + \sum_p \nu_p \bar{h}_p^{IG} - \sum_r \nu_r \bar{h}_r^{IG} = 0 \Rightarrow \bar{h}_C = \bar{h}_P(T_0) - \bar{h}_R(T_0)$$

$$\bar{h}_R = -214550.54 \text{ kJ/kmol}$$

$\bar{h}_P$ depends on T_{af} which can be calculated guessing until $\bar{h}_P = \bar{h}_R$

$T_{af} = 1158$ K

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-23 [OWU] Ethylene (C_2H_4) enters an adiabatic combustion chamber at 25°C, 1 atm and is burned with 40% excess air that enters at 25°C, 1 atm. The combustion is complete, and the products leave the combustion chamber at 1 atm. Assuming T_0 = 25°C, determine (a) the temperature (T) of the products, (b) the entropy generation and (c) the irreversibility.

SOLUTION

(a) The balanced theoretical reaction is:

$$C_2H_4 + 4.2(O_2 + 3.76\,N_2) \rightarrow +2CO_2 + 2H_2O + 1.2O_2 + 15.8N_2$$

For steady flow the energy equation is as follows:

$$\bar{h}_P - \bar{h}_R = 0$$

$$\sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r = 0$$

$$\sum_p \nu_p \bar{h}^\circ_{f,p} - \sum_r \nu_r \bar{h}^\circ_{f,r} + \sum_p \nu_p \bar{h}_p^{\mathrm{IG}} - \sum_r \nu_r \bar{h}_r^{\mathrm{IG}} = 0$$

$$\bar{h}_P(T_0) - \bar{h}_R(T_0) + \sum_p \nu_p \bar{h}_p^{\mathrm{IG}} - \sum_r \nu_r \bar{h}_r^{\mathrm{IG}} = 0 \Rightarrow \bar{h}_C = \bar{h}_P(T_0) - \bar{h}_R(T_0)$$

$$\bar{h}_R = 52383.36\ \mathrm{kJ/kmol}$$

$\bar{h}_P$ depends on T_{af} which can be calculated guessing until $\bar{h}_P = \bar{h}_R$

$$T_{af} = 2047\ \mathrm{K}$$

(b) Entropy generation:

$$\bar{S}_{gen} = \bar{S}_P - \bar{S}_R = \sum \nu_p \bar{s}_P - \sum \nu_r \bar{s}_R$$

Therefore,

$$\bar{S}_{gen} = \bar{S}_P - \bar{S}_R = 5618.2 - 4209.26 = 1408.9\ \mathrm{kJ/kmol\cdot K}$$

(c) Irreversibility:

$$X_{destroyed} = T_o \bar{S}_{gen} = (298)(1408.9) = 420074.19\ \mathrm{kJ/kmol}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-24 [OWX] Calculate the enthalpy of combustion ($\Delta h^o{}_C$) of gaseous methane, in kJ per kg of fuel, (a) at 25^{o}C, 100 kPa with water vapor in the products, (b) at 25^{o}C, 100 kPa with liquid water in the products. (c) What-if Scenario: What would the enthalpy in part (a) be at 850 K, 1 atm?

SOLUTION

The balanced theoretical reaction is:

$$CH_4 + 2.5\,(O_2 + 3.76\,N_2) \rightarrow + CO_2\ + 2H_2O + 7.5N_2$$

(a) Enthalpy of combustion with water vapor:

$$\overline{\Delta h_C} = \overline{h_P} - \overline{h_R}$$

$$\overline{\Delta h_C} = -877257.28 - (-74866.28) = -802390.98\,\text{kJ/kmol}$$

$$\Delta h_C = \frac{-802390.98}{16} = -50149.43\,\text{kJ/kg}$$

(b) Enthalpy of combustion with liquid water:

$$\overline{\text{HHV}} = \overline{\text{LHV}} + \nu_{H_2O}\overline{h}_{fg,H_2O} = 802390.98 + 2(18)2442.3$$

$$\overline{\text{HHV}} = 890314.86\,\text{kJ/kmol}$$

$$\text{HHV} = \frac{890314.86}{44} = 55644.6\,\text{kJ/kg}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-25 [OWV] Ethylene burns with 50% excess air, both entering at 25^{o}C, 100 kPa and the product exiting at the same temperature and pressure. Determine (a) the lower heating value, (b) the higher heating value and (c) the heat transfer per kmol of fuel without assuming complete vapor or complete liquid in the product.

SOLUTION

The balanced theoretical reaction is:

$$C_2H_4 + 4.5\,(O_2 + 3.76\,N_2) \rightarrow +\ 2\,CO_2\ + 2\ H_2O + 1.5O_2 + 16.92\,N_2$$

(a) Lower heating value:

$$\overline{\text{LHV}} = -\overline{\Delta h_C} = \bar{h}_R - \bar{h}_P = 1270911.1 + (52477.7) = 1323.38\ \text{MW/kmol}$$

(b) Higher heating value:

$$\overline{\text{HHV}} = \overline{\text{LHV}} + v_{H_2O}\,\bar{h}_{fg,H_2O} = 1323.38 + 2(18)(2.442) = 1411.3\text{MW}$$

(c) Heat transfer:

$$-\dot{Q}_{out} = \bar{h}_P - \bar{h}_R$$

$$-\dot{Q}_{out} = -1270911.1 - (52477.7)$$

$$\dot{Q}_{out} = -1323.38\ \ \text{MW/kmol}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-26 [OWQ] Propane burns with theoretical amount air, both entering at 25^{o}C, 100 kPa and the product exiting at the same temperature and pressure. Determine (a) the lower heating value (LHV) and (b) the higher heating value (HHV). (c) What-if Scenario: What would the lower heating value be if liquid propane were used?

SOLUTION

The balanced theoretical reaction is:

$$C_3H_8 + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

Balancing the equation yields;

$$C_3H_8 + 4.78(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18N_2$$

(a) The lower heating value:

$$\overline{\mathrm{LHV}} = -\overline{\Delta h_c^o}$$
$$\overline{\Delta h_c^o} = \overline{h_P} - \overline{h_R} = -2148079.6 - (104178.7)$$
$$\Rightarrow \overline{\Delta h_c^o} = -2043900.9 \text{ kJ/kmol}$$
$$\overline{\mathrm{LHV}} = 2043900.9 \text{ kJ/kmol}$$
$$\mathrm{LHV} = \frac{2043900.9}{44} = 46452.3 \text{ kJ/kg}$$

(b) The higher heating value:

$$\overline{\mathrm{HHV}} = \overline{\mathrm{LHV}} + \nu_{H_2O}\overline{h}_{fg,H_2O} = 2043900.9 + 4(18)2442.3$$
$$\overline{\mathrm{HHV}} = 2219746.5 \text{ kJ/kmol}$$
$$\mathrm{HHV} = \frac{2219746.5}{44} = 50448.78 \text{ kJ/kg}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-27 [OWT] Octane gas (C_8H_{18}) at 25°C is burned steadily with 50% excess air at 25°C, 100 kPa and 40% relative humidity. Assuming combustion is complete and the products leave the combustion chamber at 800 K, determine (a) the heat transfer ($\bar{q}$) for this process. (b) What-if Scenario: What would the heat transfer be if hexane (C_6H_{14}) were used?

SOLUTION

The balanced theoretical reaction is:

$$\mathrm{C_8H_{18} + 23.7(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 70.5N_2 + 6.2O_2}$$

(a) The heat transfer rate:

$$-\dot{Q}_{out} = \overline{h_P} - \overline{h_R}$$
$$-\dot{Q}_{out} = -3812422.1 - (208402.5)$$
$$\dot{Q}_{out} = -3604019.6 \text{ kJ/kmol}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-28 [OWY] Liquid octane (C_8H_{18}) enters an internal combustion engine operating at steady state with a mass flow rate of 0.002 kg/s and is mixed with 10% excess air. Fuel and air enter the engine at 25°C, 1 atm and the products leave the engine at 500 K. The engine develops a power output of 40 kW. (a) Assuming complete combustion and neglecting KE and PE effects, determine the rate of heat transfer from the engine. Use the PG mixture model. (b) What-if Scenario: What would the rate of heat transfer be if the IG mixture model were used?

SOLUTION

The balanced theoretical reaction is:

$$C_8H_{18} + 13.75\,(O_2 + 3.76\,N_2) \rightarrow +8\,CO_2 + 9H_2O + 1.2O_2 + 51.72\,N_2$$

(a) The rate of heat transfer is:

The energy equation to be used is;

$$\dot{Q} - \dot{W}_{ext} = h_P - h_R$$

$$\dot{Q} = -85.7 - (-4.37) + 40$$

$$\dot{Q} = -41.3 \text{ KW}$$

TEST Verification: Use the n-PG non-premixed combustion TESTcalc to verify the results.

13-2-29 [OWF] Liquid octane (C_8H_{18}) enters an internal combustion engine operating at steady state with a mass flow rate of 0.002 kg/s and is mixed with 20% excess air. Fuel and air enter the engine at 25°C, 1 atm and the products leave the engine at 500 K. The engine develops a power output of 35 kW. Assuming complete combustion and neglecting KE and PE effects, determine the rate of heat transfer from the engine. Use the IG mixture model.

SOLUTION

The balanced theoretical reaction is:

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

The reaction with 20% excess air is:

$$C_8H_{18}(l) + 15\left(O_2 + 3.76N_2\right) \rightarrow 8CO_2 + 9H_2O + 56.43N_2 + 2.5O_2$$

The energy balance for the combustor is given by:

$$\dot{Q} - \dot{W}_{ext} = h_P - h_R$$

$$\dot{Q} = -84.85 - (-4.37) + 35$$

$$\dot{Q} = -45.47 \text{ kW}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-30 [OWD] Repeat problem *13-2-29 [OWF] for 10% excess air. (b) What-if Scenario: What would the answer be if the reactor pressure were 50 atm?

SOLUTION

The balanced theoretical reaction is:

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

The reaction with 10% excess air is:

$$C_8H_{18(l)} + 13.75\left(O_2 + 3.76N_2\right) \rightarrow 8CO_2 + 9H_2O + 1.25O_2 + 51.7N_2$$

The energy balance for the combustor is given by:

$$\dot{Q} - \dot{W}_{ext} = h_P - h_R$$
$$\dot{Q} = -85.47 - (-4.37) + 35$$
$$\dot{Q} = -46.1 \text{ kW}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-31 [OWM] Repeat problem *13-2-29 [OWF] for 10% deficient air.

SOLUTION

The balanced reaction equation is:

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

The reaction with 10% deficient air is:

$$C_8H_{18}(l) + 11.25(O_2 + 3.76N_2) \rightarrow 7.2CO_2 + 8.1H_2O + 42.32N_2 + 0.01C_8H_{18}(g)$$

The energy balance for the combustor is given by:

$$\dot{Q} - \dot{W}_{ext} = h_P - h_R$$
$$\dot{Q} = -77.85 - (-4.37) + 35$$
$$\dot{Q} = -38.47 \text{ kW}$$

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.

13-2-32 [BVZ] Octane (C_8H_{18}) at 25^{o}C, 100 kPa enters a combustion chamber and reacts with 100% theoretical air entering at the same conditions. Determine the adiabatic flame temperature assuming the complete combustion. Use the combustion RIA linked from the left margin. (c) What-if Scenario: How would the answer change if the air flow is increased to 120% theoretical air?

SOLUTION

The balanced reaction equation is:

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

When calculating adiabatic flame temperature;

$$\bar{h}_P - \bar{h}_R = 0$$

$$\sum_p \nu_p \bar{h}_p - \sum_r \nu_r \bar{h}_r = 0$$

$$\sum_p \nu_p \bar{h}^\circ{}_{f,p} - \sum_r \nu_r \bar{h}^\circ{}_{f,r} + \sum_p \nu_p \bar{h}_p^{\mathrm{IG}} - \sum_r \nu_r \bar{h}_r^{\mathrm{IG}} = 0$$

$$\bar{h}_P(T_0) - \bar{h}_R(T_0) + \sum_p \nu_p \bar{h}_p^{\mathrm{IG}} - \sum_r \nu_r \bar{h}_r^{\mathrm{IG}} = 0 \Rightarrow \bar{h}_C = \bar{h}_P(T_0) - \bar{h}_R(T_0)$$

$$\bar{h}_R = -189.92 \text{ kJ/kmol}$$

$\bar{h}_P$ depends on T_{af} which can be calculated guessing until $\bar{h}_P = \bar{h}_R$;

T_{af} = 2411.5 K

TEST Verification: Use the n-IG non-premixed combustion TESTcalc to verify the results.