
First Law Analysis of Reacting Systems

15-46C In this case $\Delta U + W_b = \Delta H$, and the conservation of energy relation reduces to the form of the steady-flow energy relation.

15-47C The heat transfer will be the same for all cases. The excess oxygen and nitrogen enters and leaves the combustion chamber at the same state, and thus has no effect on the energy balance.

15-48C For case (b), which contains the maximum amount of nonreacting gases. This is because part of the chemical energy released in the combustion chamber is absorbed and transported out by the nonreacting gases.

15-49 Methane is burned completely during a steady-flow combustion process. The heat transfer from the combustion chamber is to be determined for two cases.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

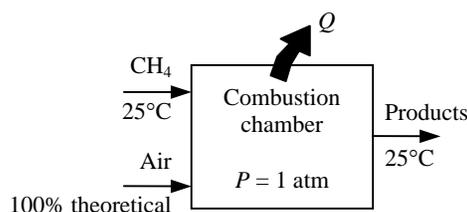
Analysis The fuel is burned completely with the stoichiometric amount of air, and thus the products will contain only H_2O , CO_2 and N_2 , but no free O_2 . Considering 1 kmol of fuel, the theoretical combustion equation can be written as



where a_{th} is determined from the O_2 balance,

$$a_{\text{th}} = 1 + 1 = 2$$

Substituting,



The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P \bar{h}_{f,P}^\circ - \sum N_R \bar{h}_{f,R}^\circ$$

since both the reactants and the products are at 25°C and both the air and the combustion gases can be treated as ideal gases. From the tables,

Substance	\bar{h}_f° kJ/kmol
CH_4	-74,850
O_2	0
N_2	0
$\text{H}_2\text{O} (\ell)$	-285,830
CO_2	-393,520

Thus,

$$-Q_{\text{out}} = (1)(-393,520) + (2)(-285,830) + 0 - (1)(-74,850) - 0 - 0 = -890,330 \text{ kJ / kmol CH}_4$$

or

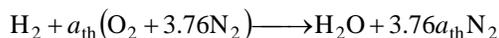
$$Q_{\text{out}} = \mathbf{890,330 \text{ kJ / kmol CH}_4}$$

If combustion is achieved with 100% excess air, the answer would still be the same since it would enter and leave at 25°C , and absorb no energy.

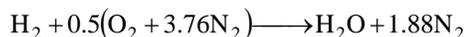
15-50 Hydrogen is burned completely during a steady-flow combustion process. The heat transfer from the combustion chamber is to be determined for two cases.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

Analysis The H_2 is burned completely with the stoichiometric amount of air, and thus the products will contain only H_2O and N_2 , but no free O_2 . Considering 1 kmol of H_2 , the theoretical combustion equation can be written as



where a_{th} is determined from the O_2 balance to be $a_{\text{th}} = 0.5$. Substituting,



The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on

the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P \bar{h}_{f,P} - \sum N_R \bar{h}_{f,R}$$

since both the reactants and the products are at 25°C and both the air and the combustion gases can be treated as ideal gases. From the tables,

Substance	\bar{h}_f° kJ/kmol
H_2	0
O_2	0
N_2	0
$\text{H}_2\text{O} (\ell)$	-285,830

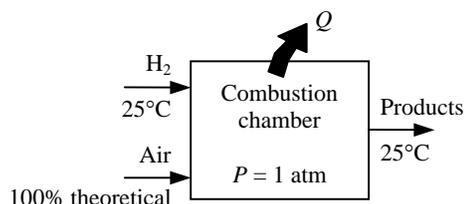
Substituting,

$$-Q_{\text{out}} = (1)(-285,830) + 0 - 0 - 0 - 0 = -285,830 \text{ kJ / kmol H}_2$$

or

$$Q_{\text{out}} = \mathbf{285,830 \text{ kJ / kmol H}_2}$$

If combustion is achieved with 50% excess air, the answer would still be the same since it would enter and leave at 25°C , and absorb no energy.



15-51 Liquid propane is burned with 150 percent excess air during a steady-flow combustion process. The mass flow rate of air and the rate of heat transfer from the combustion chamber are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

Properties The molar masses of propane and air are 44 kg/kmol and 29 kg/kmol, respectively (Table A-1).

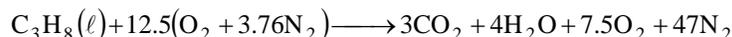
Analysis The fuel is burned completely with excess air, and thus the products will contain only CO_2 , H_2O , N_2 , and some free O_2 . Considering 1 kmol of C_3H_8 , the combustion equation can be written as



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$2.5a_{\text{th}} = 3 + 2 + 1.5a_{\text{th}} \longrightarrow a_{\text{th}} = 5$$

Thus,



(a) The air-fuel ratio for this combustion process is

$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{(12.5 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{(3 \text{ kmol})(12 \text{ kg/kmol}) + (4 \text{ kmol})(2 \text{ kg/kmol})} = 39.22 \text{ kg air/kg fuel}$$

Thus, $\dot{m}_{\text{air}} = (\text{AF})(\dot{m}_{\text{fuel}}) = (39.22 \text{ kg air/kg fuel})(1.2 \text{ kg fuel/min}) = \mathbf{47.1 \text{ kg air/min}}$

(b) The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R$$

Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{285 \text{ K}}$ kJ/kmol	$\bar{h}_{298 \text{ K}}$ kJ/kmol	$\bar{h}_{1200 \text{ K}}$ kJ/kmol
$\text{C}_3\text{H}_8(\ell)$	-118,910	---	---	---
O_2	0	8296.5	8682	38,447
N_2	0	8286.5	8669	36,777
$\text{H}_2\text{O}(g)$	-241,820	---	9904	44,380
CO_2	-393,520	---	9364	53,848

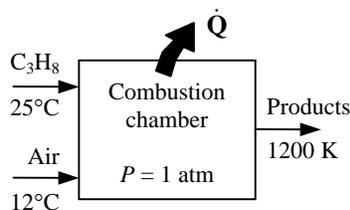
The \bar{h}_f° of liquid propane is obtained by adding \bar{h}_{fg} of propane at 25°C to \bar{h}_f° of gas propane. Substituting,

$$\begin{aligned} -Q_{\text{out}} &= (3)(-393,520 + 53,848 - 9364) + (4)(-241,820 + 44,380 - 9904) + (7.5)(0 + 38,447 - 8682) \\ &\quad + (47)(0 + 36,777 - 8669) - (1)(-118,910 + h_{298} - h_{298}) - (12.5)(0 + 8296.5 - 8682) \\ &\quad - (47)(0 + 8286.5 - 8669) \\ &= -190,464 \text{ kJ/kmol C}_3\text{H}_8 \end{aligned}$$

or $Q_{\text{out}} = 190,464 \text{ kJ/kmol C}_3\text{H}_8$

Then the rate of heat transfer for a mass flow rate of 1.2 kg/min for the propane becomes

$$\dot{Q}_{\text{out}} = \dot{N} Q_{\text{out}} = \left(\frac{\dot{m}}{N} \right) Q_{\text{out}} = \left(\frac{1.2 \text{ kg/min}}{44 \text{ kg/kmol}} \right) (190,464 \text{ kJ/kmol}) = \mathbf{5194 \text{ kJ/min}}$$



15-52E Liquid propane is burned with 150 percent excess air during a steady-flow combustion process. The mass flow rate of air and the rate of heat transfer from the combustion chamber are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

Properties The molar masses of propane and air are 44 lbm/lbmol and 29 lbm/lbmol, respectively (Table A-1E).

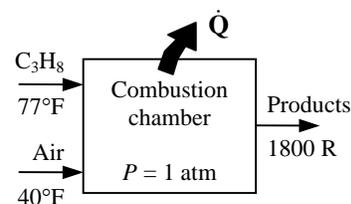
Analysis The fuel is burned completely with the excess air, and thus the products will contain only CO_2 , H_2O , N_2 , and some free O_2 . Considering 1 kmol of C_3H_8 , the combustion equation can be written as



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$2.5a_{\text{th}} = 3 + 2 + 1.5a_{\text{th}} \longrightarrow a_{\text{th}} = 5$$

Thus,



(a) The air-fuel ratio for this combustion process is

$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{(12.5 \times 4.76 \text{ lbmol})(29 \text{ lbm/lbmol})}{(3 \text{ lbmol})(12 \text{ lbm/lbmol}) + (4 \text{ lbmol})(2 \text{ lbm/lbmol})} = 39.2 \text{ lbmair/lbmfuel}$$

Thus, $\dot{m}_{\text{air}} = (\text{AF})(\dot{m}_{\text{fuel}}) = (39.2 \text{ lbm air/lbm fuel})(0.75 \text{ lbm fuel/min}) = \mathbf{29.4 \text{ lbm air / min}}$

(b) The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R$$

Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	\bar{h}_f° Btu/lbmol	$\bar{h}_{500\text{R}}$ Btu/lbmol	$\bar{h}_{537\text{R}}$ Btu/lbmol	$\bar{h}_{1800\text{R}}$ Btu/lbmol
$\text{C}_3\text{H}_8(\ell)$	-51,160	---	---	---
O_2	0	3466.2	3725.1	13,485.8
N_2	0	3472.2	3729.5	12,956.3
CO_2	-169,300	---	4027.5	18,391.5
$\text{H}_2\text{O}(g)$	-104,040	---	4258.0	15,433.0

The \bar{h}_f° of liquid propane is obtained by adding the \bar{h}_{fg} of propane at 77°F to the \bar{h}_f° of gas propane. Substituting,

$$\begin{aligned} -Q_{\text{out}} &= (3)(-169,300 + 18,391.5 - 4027.5) + (4)(-104,040 + 15,433 - 4258) + (7.5)(0 + 13,485.8 - 3725.1) \\ &\quad + (47)(0 + 12,959.3 - 3729.5) - (1)(-51,160 + h_{537} - h_{537}) - (12.5)(0 + 3466.2 - 3725.1) \\ &\quad - (47)(0 + 3472.2 - 3729.5) \\ &= -262,773 \text{ Btu / lbmol C}_3\text{H}_8 \end{aligned}$$

or $Q_{\text{out}} = 262,773 \text{ Btu / lbmol C}_3\text{H}_8$

Then the rate of heat transfer for a mass flow rate of 0.75 kg/min for the propane becomes

$$\dot{Q}_{\text{out}} = \dot{N} Q_{\text{out}} = \left(\frac{\dot{m}}{N} \right) Q_{\text{out}} = \left(\frac{0.75 \text{ lbm/min}}{44 \text{ lbm/lbmol}} \right) (262,773 \text{ Btu/lbmol}) = \mathbf{4479 \text{ Btu/min}}$$

15-53 Acetylene gas is burned with 20 percent excess air during a steady-flow combustion process. The AF ratio and the heat transfer are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

Properties The molar masses of C_2H_2 and air are 26 kg/kmol and 29 kg/kmol, respectively (Table A-1).

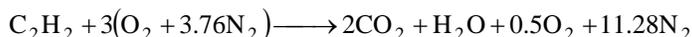
Analysis The fuel is burned completely with the excess air, and thus the products will contain only CO_2 , H_2O , N_2 , and some free O_2 . Considering 1 kmol of C_2H_2 , the combustion equation can be written as



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$1.2a_{th} = 2 + 0.5 + 0.2a_{th} \longrightarrow a_{th} = 2.5$$

Thus,



$$(a) \quad AF = \frac{m_{air}}{m_{fuel}} = \frac{(3 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{(2 \text{ kmol})(12 \text{ kg/kmol}) + (1 \text{ kmol})(2 \text{ kg/kmol})} = \mathbf{15.9 \text{ kg air/kg fuel}}$$

(b) The heat transfer for this combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R \bar{h}_{f,R}^\circ$$

since all of the reactants are at 25°C. Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

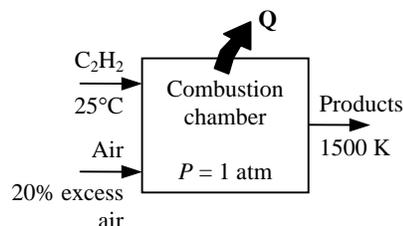
Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{298 \text{ K}}$ kJ/kmol	$\bar{h}_{1500 \text{ K}}$ kJ/kmol
C_2H_2	226,730	---	---
O_2	0	8682	49,292
N_2	0	8669	47,073
$H_2O(g)$	-241,820	9904	57,999
CO_2	-393,520	9364	71,078

Thus,

$$\begin{aligned} -Q_{out} &= (2)(-393,520 + 71,078 - 9364) + (1)(-241,820 + 57,999 - 9904) + (0.5)(0 + 49,292 - 8682) \\ &\quad + (11.28)(0 + 47,073 - 8669) - (1)(226,730) - 0 - 0 \\ &= \mathbf{-630,565 \text{ kJ/kmol } C_2H_2} \end{aligned}$$

or

$$Q_{out} = \mathbf{630,565 \text{ kJ / kmol } C_2H_2}$$



15-54E Liquid octane is burned with 180 percent theoretical air during a steady-flow combustion process. The AF ratio and the heat transfer from the combustion chamber are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

Properties The molar masses of C_8H_{18} and air are 54 kg/kmol and 29 kg/kmol, respectively (Table A-1).

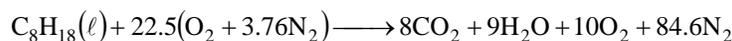
Analysis The fuel is burned completely with the excess air, and thus the products will contain only CO_2 , H_2O , N_2 , and some free O_2 . Considering 1 kmol of C_8H_{18} , the combustion equation can be written as



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$1.8a_{th} = 8 + 4.5 + 0.8a_{th} \longrightarrow a_{th} = 12.5$$

Thus,



$$(a) \quad AF = \frac{m_{air}}{m_{fuel}} = \frac{(22.5 \times 4.76 \text{ lbmol})(29 \text{ lbm/lbmol})}{(8 \text{ lbmol})(12 \text{ lbm/lbmol}) + (9 \text{ lbmol})(2 \text{ lbm/lbmol})} = \mathbf{27.2 \text{ lbmair/lbmfuel}}$$

(b) The heat transfer for this combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R \bar{h}_{f,R}^\circ$$

since all of the reactants are at 77°F. Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

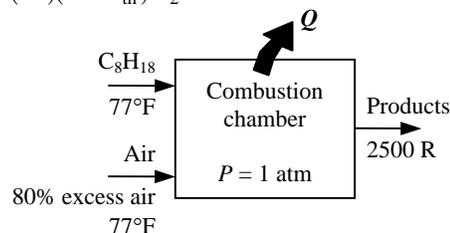
Substance	\bar{h}_f° Btu/lbmol	$\bar{h}_{537 R}$ Btu/lbmol	$\bar{h}_{2500 R}$ Btu/lbmol
$C_8H_{18}(\ell)$	-107,530	---	---
O_2	0	3725.1	19,443
N_2	0	3729.5	18,590
CO_2	-169,300	4027.5	27,801
$H_2O(g)$	-104,040	4258.0	22,735

Thus,

$$\begin{aligned} -Q_{out} &= (8)(-169,300 + 27,801 - 4027.5) + (9)(-104,040 + 22,735 - 4258) + (10)(0 + 19,443 - 3725.1) \\ &\quad + (84.6)(0 + 18,590 - 3729.5) - (1)(-107,530) - 0 - 0 \\ &= \mathbf{-412,372 \text{ Btu/lbmol } C_8H_{18}} \end{aligned}$$

or

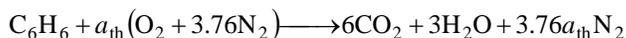
$$Q_{out} = \mathbf{412,372 \text{ Btu/lbmol } C_8H_{18}}$$



15-55 Benzene gas is burned with 95 percent theoretical air during a steady-flow combustion process. The mole fraction of the CO in the products and the heat transfer from the combustion chamber are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible.

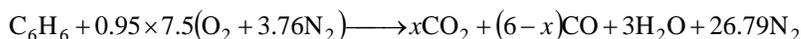
Analysis (a) The fuel is burned with insufficient amount of air, and thus the products will contain some CO as well as CO₂, H₂O, and N₂. The theoretical combustion equation of C₆H₆ is



where a_{th} is the stoichiometric coefficient and is determined from the O₂ balance,

$$a_{\text{th}} = 6 + 1.5 = 7.5$$

Then the actual combustion equation can be written as



$$\text{O}_2 \text{ balance: } 0.95 \times 7.5 = x + (6-x)/2 + 1.5 \longrightarrow x = 5.25$$



The mole fraction of CO in the products is

$$y_{\text{CO}} = \frac{N_{\text{CO}}}{N_{\text{total}}} = \frac{0.75}{5.25 + 0.75 + 3 + 26.79} = 0.021 \text{ or } \mathbf{2.1\%}$$

(b) The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R \bar{h}_{f,R}^\circ$$

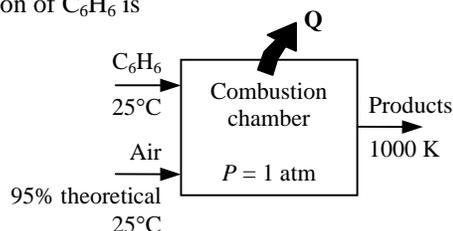
since all of the reactants are at 25°C. Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{298\text{ K}}$ kJ/kmol	$\bar{h}_{1000\text{ K}}$ kJ/kmol
C ₆ H ₆ (g)	82,930	---	---
O ₂	0	8682	31,389
N ₂	0	8669	30,129
H ₂ O (g)	-241,820	9904	35,882
CO	-110,530	8669	30,355
CO ₂	-393,520	9364	42,769

Thus,

$$\begin{aligned} -Q_{\text{out}} &= (5.25)(-393,520 + 42,769 - 9364) + (0.75)(-110,530 + 30,355 - 8669) \\ &\quad + (3)(-241,820 + 35,882 - 9904) + (26.79)(0 + 30,129 - 8669) - (1)(82,930) - 0 - 0 \\ &= -2,112,779 \text{ kJ / kmol C}_6\text{H}_6 \end{aligned}$$

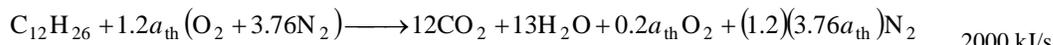
$$\text{or } \dot{Q}_{\text{out}} = \mathbf{2,112,800 \text{ kJ/kmol C}_6\text{H}_6}$$



15-56 Diesel fuel is burned with 20 percent excess air during a steady-flow combustion process. The required mass flow rate of the diesel fuel to supply heat at a specified rate is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

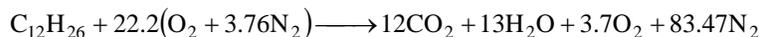
Analysis The fuel is burned completely with the excess air, and thus the products will contain only CO_2 , H_2O , N_2 , and some free O_2 . Considering 1 kmol of $\text{C}_{12}\text{H}_{26}$, the combustion equation can be written as



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$1.2a_{\text{th}} = 12 + 6.5 + 0.2a_{\text{th}} \longrightarrow a_{\text{th}} = 18.5$$

Substituting,



The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R \bar{h}_{f,R}^\circ$$

since all of the reactants are at 25°C . Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{298\text{ K}}$ kJ/kmol	$\bar{h}_{500\text{ K}}$ kJ/kmol
$\text{C}_{12}\text{H}_{26}$	-291,010	---	---
O_2	0	8682	14,770
N_2	0	8669	14,581
$\text{H}_2\text{O} (g)$	-241,820	9904	16,828
CO_2	-393,520	9364	17,678

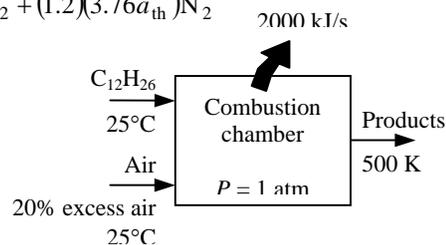
Thus,

$$\begin{aligned} -Q_{\text{out}} &= (12)(-393,520 + 17,678 - 9364) + (13)(-241,820 + 16,828 - 9904) \\ &\quad + (3.7)(0 + 14,770 - 8682) + (83.47)(0 + 14,581 - 8669) - (1)(-291,010) - 0 - 0 \\ &= -6,869,110 \text{ kJ/kmol } \text{C}_{12}\text{H}_{26} \end{aligned}$$

or $\dot{Q}_{\text{out}} = 6,869,110 \text{ kJ/kmol } \text{C}_{12}\text{H}_{26}$

Then the required mass flow rate of fuel for a heat transfer rate of 2000 kJ/s becomes

$$\dot{m} = \dot{N}M = \left(\frac{\dot{Q}_{\text{out}}}{Q_{\text{out}}} \right) M = \left(\frac{2000 \text{ kJ/s}}{6,869,110 \text{ kJ/kmol}} \right) (170 \text{ kg/kmol}) = 0.0495 \text{ kg/s} = \mathbf{49.5 \text{ g/s}}$$



15-57E Diesel fuel is burned with 20 percent excess air during a steady-flow combustion process. The required mass flow rate of the diesel fuel for a specified heat transfer rate is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

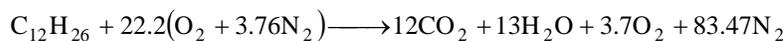
Analysis The fuel is burned completely with the excess air, and thus the products will contain only CO_2 , H_2O , N_2 , and some free O_2 . Considering 1 kmol of $\text{C}_{12}\text{H}_{26}$, the combustion equation can be written as



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$1.2a_{\text{th}} = 12 + 6.5 + 0.2a_{\text{th}} \longrightarrow a_{\text{th}} = 18.5$$

Substituting,



The heat transfer for this combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R \bar{h}_{f,R}^\circ$$

since all of the reactants are at 77°F . Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	\bar{h}_f° Btu/lbmol	$\bar{h}_{537\text{ R}}$ Btu/lbmol	$\bar{h}_{800\text{ R}}$ Btu/lbmol
$\text{C}_{12}\text{H}_{26}$	-125,190	---	---
O_2	0	3725.1	5602.0
N_2	0	3729.5	5564.4
$\text{H}_2\text{O} (g)$	-104,040	4258.0	6396.9
CO_2	-169,300	4027.5	6552.9

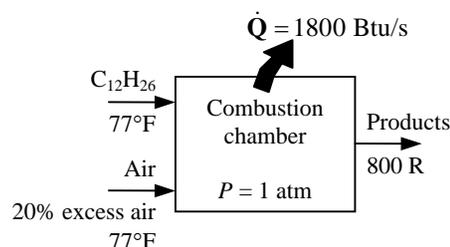
Thus,

$$\begin{aligned} -Q_{\text{out}} &= (12)(-169,300 + 6552.9 - 4027.5) + (13)(-104,040 + 6396.9 - 4258) \\ &\quad + (3.7)(0 + 5602.0 - 3725.1) + (83.47)(0 + 5564.4 - 3729.5) - (1)(-125,190) - 0 - 0 \\ &= -3,040,716 \text{ Btu/lbmol } \text{C}_{12}\text{H}_{26} \end{aligned}$$

or $Q_{\text{out}} = 3,040,716 \text{ Btu/lbmol } \text{C}_{12}\text{H}_{26}$

Then the required mass flow rate of fuel for a heat transfer rate of 1800 Btu/s becomes

$$\dot{m} = \dot{N}M = \left(\frac{\dot{Q}}{Q}\right)M = \left(\frac{1800 \text{ Btu/s}}{3,040,716 \text{ Btu/lbmol}}\right)(170 \text{ lbm/lbmol}) = \mathbf{0.1006 \text{ lbm/s}}$$



15-58 [Also solved by EES on enclosed CD] Octane gas is burned with 30 percent excess air during a steady-flow combustion process. The heat transfer per unit mass of octane is to be determined.

Assumptions 1 Steady operating conditions exist. **2** Air and combustion gases are ideal gases. **3** Kinetic and potential energies are negligible. **4** Combustion is complete.

Properties The molar mass of C_8H_{18} is 114 kg/kmol (Table A-1).

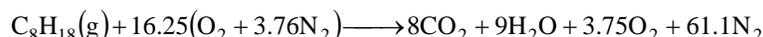
Analysis The fuel is burned completely with the excess air, and thus the products will contain only CO_2 , H_2O , N_2 , and some free O_2 . The moisture in the air does not react with anything; it simply shows up as additional H_2O in the products. Therefore, for simplicity, we will balance the combustion equation using dry air, and then add the moisture to both sides of the equation. Considering 1 kmol of C_8H_{18} , the combustion equation can be written as



where a_{th} is the stoichiometric coefficient for air. It is determined from

$$O_2 \text{ balance: } 1.3a_{th} = 8 + 4.5 + 0.3a_{th} \longrightarrow a_{th} = 12.5$$

Thus,



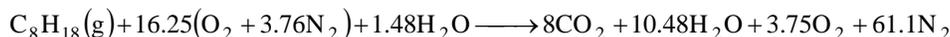
Therefore, $16.25 \times 4.76 = 77.35$ kmol of dry air will be used per kmol of the fuel. The partial pressure of the water vapor present in the incoming air is

$$P_{v,in} = \phi_{air} P_{sat@25^\circ C} = (0.60)(3.1698 \text{ kPa}) = 1.902 \text{ kPa}$$

Assuming ideal gas behavior, the number of moles of the moisture that accompanies 77.35 kmol of incoming dry air is determined to be

$$N_{v,in} = \left(\frac{P_{v,in}}{P_{total}} \right) N_{total} = \left(\frac{1.902 \text{ kPa}}{101.325 \text{ kPa}} \right) (77.35 + N_{v,in}) \longrightarrow N_{v,in} = 1.48 \text{ kmol}$$

The balanced combustion equation is obtained by adding 1.48 kmol of H_2O to both sides of the equation,



The heat transfer for this combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R \bar{h}_{f,R}^\circ$$

since all of the reactants are at $25^\circ C$. Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

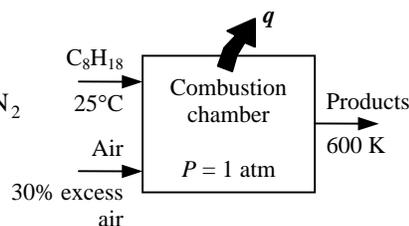
Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{298 \text{ K}}$ kJ/kmol	$\bar{h}_{600 \text{ K}}$ kJ/kmol
$C_8H_{18}(g)$	-208,450	---	---
O_2	0	8682	17,929
N_2	0	8669	17,563
$H_2O(g)$	-241,820	9904	20,402
CO_2	-393,520	9364	22,280

Substituting,

$$\begin{aligned} -Q_{out} &= (8)(-393,520 + 22,280 - 9364) + (10.48)(-241,820 + 20,402 - 9904) \\ &\quad + (3.75)(0 + 17,929 - 8682) + (61.1)(0 + 17,563 - 8669) \\ &\quad - (1)(-208,450) - (1.48)(-241,820) - 0 - 0 \\ &= -4,324,643 \text{ kJ/kmol } C_8H_{18} \end{aligned}$$

Thus 4,324,643 kJ of heat is transferred from the combustion chamber for each kmol (114 kg) of C_8H_{18} . Then the heat transfer per kg of C_8H_{18} becomes

$$q = \frac{Q_{out}}{M} = \frac{4,324,643 \text{ kJ}}{114 \text{ kg}} = 37,935 \text{ kJ/kg } C_8H_{18}$$



15-59 EES Problem 15-58 is reconsidered. The effect of the amount of excess air on the heat transfer for the combustion process is to be investigated.

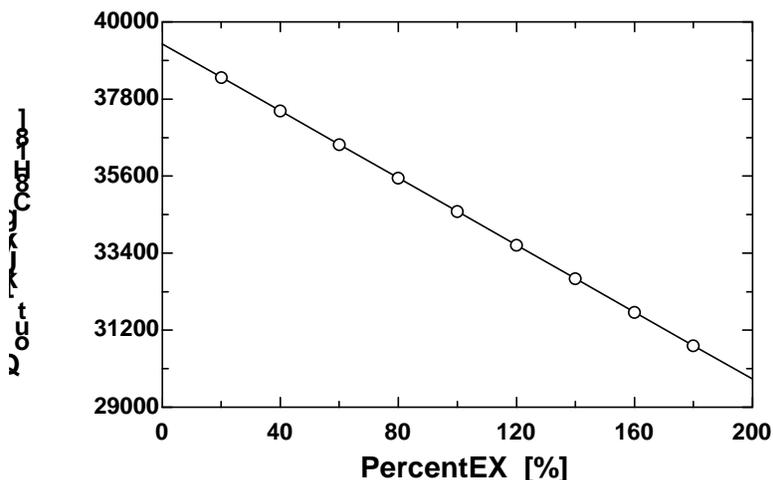
Analysis The problem is solved using EES, and the solution is given below.

```

Fuel$ = 'Octane (C8H18)'
T_fuel = (25+273) "[K]"
{PercentEX = 30 "[%"]}
Ex = PercentEX/100 "[%Excess air/100]"
P_air1 = 101.3 [kPa]
T_air1 = 25+273 "[K]"
RH_1 = 60/100 "[%]"
T_prod = 600 [K]
M_air = 28.97 [kg/kmol]
M_water = 18 [kg/kmol]
M_C8H18=(8*12+18*1) "[kg/kmol]"
"For theoretical dry air, the complete combustion equation is"
"C8H18 + A_th(O2+3.76 N2)=8 CO2+9 H2O + A_th (3.76) N2 "
A_th*2=8*2+9*1 "theoretical O balance"
"now to find the amount of water vapor associated with the dry air"
w_1=HUMRAT(AirH2O,T=T_air1,P=P_air1,R=RH_1) "Humidity ratio, kgv/kgd"
N_w=w_1*(A_th*4.76*M_air)/M_water "Moles of water in the atmospheric air, kmol/kmol_fuel"
"The balanced combustion equation with Ex% excess moist air is"
"C8H18 + (1+EX)[A_th(O2+3.76 N2)+N_w H2O]=8 CO2+(9+(1+EX)*N_w) H2O + (1+EX) A_th
(3.76) N2+ Ex( A_th) O2 "
"Apply First Law SSSF"
H_fuel = -208450 [kJ/kmol] "from Table A-26"
HR=H_fuel+ (1+Ex)*A_th*enthalpy(O2,T=T_air1)+(1+Ex)*A_th*3.76
*enthalpy(N2,T=T_air1)+(1+Ex)*N_w*enthalpy(H2O,T=T_air1)
HP=8*enthalpy(CO2,T=T_prod)+(9+(1+Ex)*N_w)*enthalpy(H2O,T=T_prod)+(1+Ex)*A_th*3.76*
enthalpy(N2,T=T_prod)+Ex*A_th*enthalpy(O2,T=T_prod)
Q_net=(HP-HR)"kJ/kmol"/(M_C8H18 "kg/kmol") "[kJ/kg_C8H18]"
Q_out = -Q_net "[kJ/kg_C8H18]"
"this solution used the humidity ratio from psychrometric data to determine the moles of water
vapor in atmospheric air. One should calculate the moles of water contained in the atmospheric
air by the method shown in Chapter 14 which uses the relative humidity to find the partial
pressure of the water vapor and, thus, the moles of water vapor. Explore what happens to the
results as you vary the percent excess air, relative humidity, and product temperature."

```

Q _{out} [kJ/kgC8H18]	PercentEX [%]
39374	0
38417	20
37460	40
36503	60
35546	80
34588	100
33631	120
32674	140
31717	160
30760	180
29803	200



15-60 Ethane gas is burned with stoichiometric amount of air during a steady-flow combustion process. The rate of heat transfer from the combustion chamber is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

Properties The molar mass of C_2H_6 is 30 kg/kmol (Table A-1).

Analysis The theoretical combustion equation of C_2H_6 is



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$a_{th} = 2 + 1.5 = 3.5$$

Then the actual combustion equation can be written as



The heat transfer for this combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R$$

Assuming the air and the combustion products to be ideal gases, we have $h = h(T)$. From the tables,

Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{500\text{ K}}$ kJ/kmol	$\bar{h}_{298\text{ K}}$ kJ/kmol	$\bar{h}_{800\text{ K}}$ kJ/kmol
$C_2H_6(g)$	-84,680	---	---	---
O_2	0	14,770	8682	24,523
N_2	0	14,581	8669	23,714
$H_2O(g)$	-241,820	---	9904	27,896
CO	-110,530	---	8669	23,844
CO_2	-393,520	---	9364	32,179

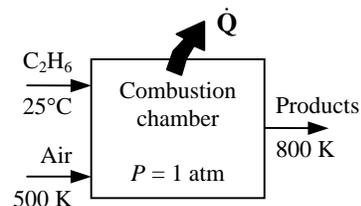
Thus,

$$\begin{aligned} -Q_{out} &= (1.9)(-393,520 + 32,179 - 9364) + (0.1)(-110,530 + 23,844 - 8669) \\ &\quad + (3)(-241,820 + 27,896 - 9904) + (0.05)(0 + 24,523 - 8682) + (13.16)(0 + 23,714 - 8669) \\ &\quad - (1)(-84,680 + h_{298} - h_{298}) - (3.5)(0 + 14,770 - 8682) - (13.16)(0 + 14,581 - 8669) \\ &= -1,201,005 \text{ kJ / kmol } C_2H_6 \end{aligned}$$

or $Q_{out} = 1,201,005 \text{ kJ / kmol } C_2H_6$

Then the rate of heat transfer for a mass flow rate of 3 kg/h for the ethane becomes

$$\dot{Q}_{out} = \dot{N} Q_{out} = \left(\frac{\dot{m}}{M} \right) Q_{out} = \left(\frac{3 \text{ kg/h}}{30 \text{ kg/kmol}} \right) (1,201,005 \text{ kJ/kmol}) = \mathbf{200,170 \text{ kJ/h}}$$



15-61 [Also solved by EES on enclosed CD] A mixture of methane and oxygen contained in a tank is burned at constant volume. The final pressure in the tank and the heat transfer during this process are to be determined.

Assumptions 1 Air and combustion gases are ideal gases. 2 Combustion is complete.

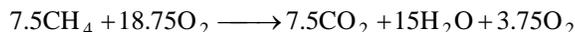
Properties The molar masses of CH₄ and O₂ are 16 kg/kmol and 32 kg/kmol, respectively (Table A-1).

Analysis (a) The combustion is assumed to be complete, and thus all the carbon in the methane burns to CO₂ and all of the hydrogen to H₂O. The number of moles of CH₄ and O₂ in the tank are

$$N_{\text{CH}_4} = \frac{m_{\text{CH}_4}}{M_{\text{CH}_4}} = \frac{0.12 \text{ kg}}{16 \text{ kg/kmol}} = 7.5 \times 10^{-3} \text{ kmol} = 7.5 \text{ mol}$$

$$N_{\text{O}_2} = \frac{m_{\text{O}_2}}{M_{\text{O}_2}} = \frac{0.6 \text{ kg}}{32 \text{ kg/kmol}} = 18.75 \times 10^{-3} \text{ kmol} = 18.75 \text{ mol}$$

Then the combustion equation can be written as



At 1200 K, water exists in the gas phase. Assuming both the reactants and the products to be ideal gases, the final pressure in the tank is determined to be

$$\left. \begin{aligned} P_R \mathcal{V} &= N_R R_u T_R \\ P_P \mathcal{V} &= N_P R_u T_P \end{aligned} \right\} P_P = P_R \left(\frac{N_P}{N_R} \right) \left(\frac{T_P}{T_R} \right)$$

Substituting,

$$P_P = (200 \text{ kPa}) \left(\frac{26.25 \text{ mol}}{26.25 \text{ mol}} \right) \left(\frac{1200 \text{ K}}{298 \text{ K}} \right) = \mathbf{805 \text{ kPa}}$$

which is relatively low. Therefore, the ideal gas assumption utilized earlier is appropriate.

(b) The heat transfer for this constant volume combustion process is determined from the energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_R$$

Since both the reactants and products are assumed to be ideal gases, all the internal energy and enthalpies depend on temperature only, and the $P\bar{v}$ terms in this equation can be replaced by $R_u T$. It yields

$$-Q_{\text{out}} = \sum N_P (\bar{h}_f^\circ + \bar{h}_{1200 \text{ K}} - \bar{h}_{298 \text{ K}} - R_u T)_P - \sum N_R (\bar{h}_f^\circ - R_u T)_R$$

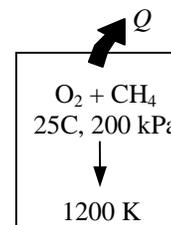
since the reactants are at the standard reference temperature of 25°C. From the tables,

Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{298 \text{ K}}$ kJ/kmol	$\bar{h}_{1200 \text{ K}}$ kJ/kmol
CH ₄	-74,850	---	---
O ₂	0	8682	38,447
H ₂ O (g)	-241,820	9904	44,380
CO ₂	-393,520	9364	53,848

Thus,

$$\begin{aligned} -Q_{\text{out}} &= (7.5)(-393,520 + 53,848 - 9364 - 8.314 \times 1200) \\ &\quad + (15)(-241,820 + 44,380 - 9904 - 8.314 \times 1200) \\ &\quad + (3.75)(0 + 38,447 - 8682 - 8.314 \times 1200) \\ &\quad - (7.5)(-74,850 - 8.314 \times 298) - (18.75)(-8.314 \times 298) \\ &= -5,251,791 \text{ J} = \mathbf{-5252 \text{ kJ}} \end{aligned}$$

Thus $Q_{\text{out}} = \mathbf{5252 \text{ kJ}}$ of heat is transferred from the combustion chamber as 120 g of CH₄ burned in this combustion chamber.



15-62 EES Problem 15-61 is reconsidered. The effect of the final temperature on the final pressure and the heat transfer for the combustion process is to be investigated.

Analysis The problem is solved using EES, and the solution is given below.

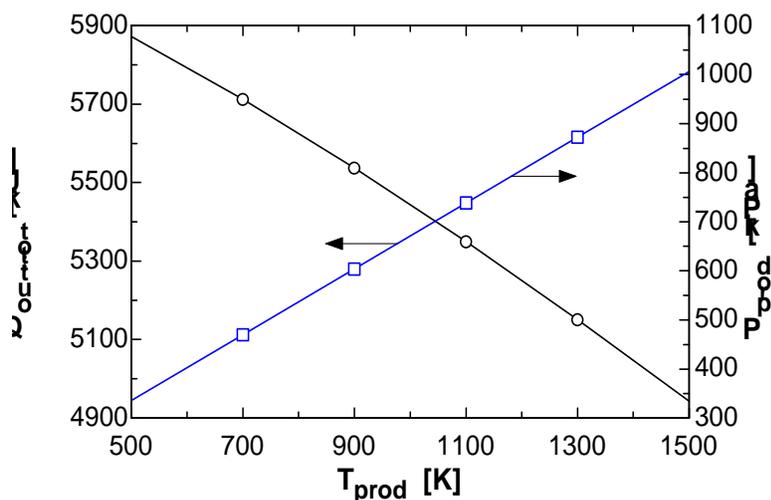
"Input Data"

```

T_reac = (25+273) "[K]"           "reactant mixture temperature"
P_reac = 200 [kPa]               "reactant mixture pressure"
{T_prod = 1200 [K]}             "product mixture temperature"
m_O2=0.600 [kg]                 "initial mass of O2"
Mw_O2 = 32 [kg/kmol]
m_CH4 = 0.120 [kg]              "initial mass of CH4"
Mw_CH4=(1*12+4*1) "[kg/kmol]"
R_u = 8.314 [kJ/kmol-K]         "universal gas constant"
"for theoretical oxygen, the complete combustion equation is"
"CH4 + A_th O2=1 CO2+2 H2O "
2*A_th=1*2+2*1"theoretical O balance"
"now to find the actual moles of O2 supplied per mole of fuel"
N_O2 = m_O2/Mw_O2/N_CH4
N_CH4= m_CH4/Mw_CH4
"The balanced complete combustion equation with Ex% excess O2 is"
"CH4 + (1+EX) A_th O2=1 CO2+ 2 H2O + Ex( A_th) O2 "
N_O2 = (1+Ex)*A_th
"Apply First Law to the closed system combustion chamber and assume ideal gas
behavior. (At 1200 K, water exists in the gas phase.)"
E_in - E_out = DELTAE_sys
E_in = 0
E_out = Q_out "kJ/kmol_CH4" "No work is done because volume is constant"
DELTA E_sys = U_prod - U_reac "neglect KE and PE and note: U = H - PV = N(h - R_u T)"
U_reac = 1*(enthalpy(CH4, T=T_reac) - R_u*T_reac) +(1+EX)*A_th*(enthalpy(O2,T=T_reac) - R_u*T_reac)
U_prod = 1*(enthalpy(CO2, T=T_prod) - R_u*T_prod) +2*(enthalpy(H2O, T=T_prod) -
R_u*T_prod)+EX*A_th*(enthalpy(O2,T=T_prod) - R_u*T_prod)
"The total heat transfer out, in kJ, is:"
Q_out_tot=Q_out"kJ/kmol_CH4"/(Mw_CH4 "kg/kmol_CH4") *m_CH4"kg" "kJ"
"The final pressure in the tank is the pressure of the product gases. Assuming
ideal gas behavior for the gases in the constant volume tank, the ideal gas law gives:"
P_reac*V=N_reac * R_u *T_reac
P_prod*V = N_prod * R_u * T_prod
N_reac = N_CH4*(1 + N_O2)
N_prod = N_CH4*(1 + 2 + Ex*A_th)

```

T _{prod} [K]	Q _{out,tot} [kJ]	P _{prod} [kPa]
500	5872	335.6
700	5712	469.8
900	5537	604
1100	5349	738.3
1300	5151	872.5
1500	4943	1007



15-63 A stoichiometric mixture of octane gas and air contained in a closed combustion chamber is ignited. The heat transfer from the combustion chamber is to be determined.

Assumptions 1 Both the reactants and products are ideal gases. **2** Combustion is complete.

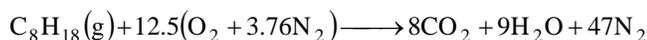
Analysis The theoretical combustion equation of C_8H_{18} with stoichiometric amount of air is



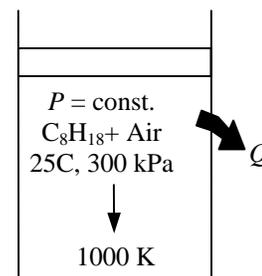
where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$a_{th} = 8 + 4.5 = 12.5$$

Thus,



The heat transfer for this constant volume combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion



chamber with $W_{other} = 0$, $-Q_{out} = \sum N_P(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_P - \sum N_R(\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_R$

For a constant pressure quasi-equilibrium process $\Delta U + W_b = \Delta H$. Then the first law relation in this case is

$$-Q_{out} = \sum N_P(\bar{h}_f^\circ + \bar{h}_{1000K} - \bar{h}_{298K})_P - \sum N_R\bar{h}_{f,R}^\circ$$

since the reactants are at the standard reference temperature of $25^\circ C$. Since both the reactants and the products behave as ideal gases, we have $h = h(T)$. From the tables,

Substance	\bar{h}_f° kJ/kmol	\bar{h}_{298K} kJ/kmol	\bar{h}_{1000K} kJ/kmol
$C_8H_{18}(g)$	-208,450	---	---
O_2	0	8682	31,389
N_2	0	8669	30,129
$H_2O(g)$	-241,820	9904	35,882
CO_2	-393,520	9364	42,769

Thus,

$$\begin{aligned} -Q_{out} &= (8)(-393,520 + 42,769 - 9364) + (9)(-241,820 + 35,882 - 9904) \\ &\quad + (47)(0 + 30,129 - 8669) - (1)(-208,450) - 0 - 0 \\ &= -3,606,428 \text{ kJ (per kmol of } C_8H_{18}) \end{aligned}$$

or $Q_{out} = 3,606,428 \text{ kJ (per kmol of } C_8H_{18})$.

Total mole numbers initially present in the combustion chamber is determined from the ideal gas relation,

$$N_1 = \frac{P_1 V_1}{R_u T_1} = \frac{(300 \text{ kPa})(0.5 \text{ m}^3)}{(8.314 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(298 \text{ K})} = 0.06054 \text{ kmol}$$

Of these, $0.06054 / (1 + 12.5 \times 4.76) = 1.001 \times 10^{-3}$ kmol of them is C_8H_{18} . Thus the amount of heat transferred from the combustion chamber as 1.001×10^{-3} kmol of C_8H_{18} is burned is

$$Q_{out} = (1.001 \times 10^{-3} \text{ kmol } C_8H_{18})(3,606,428 \text{ kJ/kmol } C_8H_{18}) = \mathbf{3610 \text{ kJ}}$$

15-64 A mixture of benzene gas and 30 percent excess air contained in a constant-volume tank is ignited. The heat transfer from the combustion chamber is to be determined.

Assumptions 1 Both the reactants and products are ideal gases. 2 Combustion is complete.

Analysis The theoretical combustion equation of C_6H_6 with stoichiometric amount of air is



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$a_{th} = 6 + 1.5 = 7.5$$

Then the actual combustion equation with 30% excess air becomes



The heat transfer for this constant volume combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_R$$

Since both the reactants and the products behave as ideal gases, all the internal energy and enthalpies depend on temperature only, and the $P\bar{v}$ terms in this equation can be replaced by $R_u T$.

It yields

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h}_{1000\text{ K}} - \bar{h}_{298\text{ K}} - R_u T)_P - \sum N_R (\bar{h}_f^\circ - R_u T)_R$$

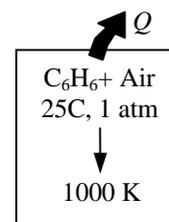
since the reactants are at the standard reference temperature of 25°C. From the tables,

Substance	\bar{h}_f° kJ/kmol	$\bar{h}_{298\text{ K}}$ kJ/kmol	$\bar{h}_{1000\text{ K}}$ kJ/kmol
$C_6H_6(g)$	82,930	---	---
O_2	0	8682	31,389
N_2	0	8669	30,129
$H_2O(g)$	-241,820	9904	35,882
CO	-110,530	8669	30,355
CO_2	-393,520	9364	42,769

Thus,

$$\begin{aligned} -Q_{out} &= (5.52)(-393,520 + 42,769 - 9364 - 8.314 \times 1000) \\ &\quad + (0.48)(-110,530 + 30,355 - 8669 - 8.314 \times 1000) \\ &\quad + (3)(-241,820 + 35,882 - 9904 - 8.314 \times 1000) \\ &\quad + (2.49)(0 + 31,389 - 8682 - 8.314 \times 1000) \\ &\quad + (36.66)(0 + 30,129 - 8669 - 8.314 \times 1000) \\ &\quad - (1)(82,930 - 8.314 \times 298) - (9.75)(4.76)(-8.314 \times 298) \\ &= -2,200,433 \text{ kJ} \end{aligned}$$

or $Q_{out} = 2,200,433 \text{ kJ}$



15-65E A mixture of benzene gas and 30 percent excess air contained in a constant-volume tank is ignited. The heat transfer from the combustion chamber is to be determined.

Assumptions 1 Both the reactants and products are ideal gases. **2** Combustion is complete.

Analysis The theoretical combustion equation of C_6H_6 with stoichiometric amount of air is



where a_{th} is the stoichiometric coefficient and is determined from the O_2 balance,

$$a_{th} = 6 + 1.5 = 7.5$$

Then the actual combustion equation with 30% excess air becomes



The heat transfer for this constant volume combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with $W = 0$. It reduces to

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ - P\bar{v})_R$$

Since both the reactants and the products behave as ideal gases, all the internal energy and enthalpies depend on temperature only, and the $P\bar{v}$ terms in this equation can be replaced by $R_u T$.

It yields

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h}_{1800R} - \bar{h}_{537R} - R_u T)_P - \sum N_R (\bar{h}_f^\circ - R_u T)_R$$

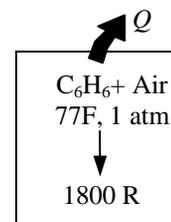
since the reactants are at the standard reference temperature of 77°F. From the tables,

Substance	\bar{h}_f° Btu/lbmol	\bar{h}_{537R} Btu/lbmol	\bar{h}_{1800R} Btu/lbmol
$C_6H_6(g)$	35,6860	---	---
O_2	0	3725.1	13,485.8
N_2	0	3729.5	12,956.3
$H_2O(g)$	-104,040	4258.0	15,433.0
CO	-47,540	3725.1	13,053.2
CO_2	-169,300	4027.5	18,391.5

Thus,

$$\begin{aligned} -Q_{out} &= (5.52)(-169,300 + 18,391.5 - 4027.5 - 1.986 \times 1800) \\ &\quad + (0.48)(-47,540 + 13,053.2 - 3725.1 - 1.986 \times 1800) \\ &\quad + (3)(-104,040 + 15,433.0 - 4258.0 - 1.986 \times 1800) \\ &\quad + (2.49)(0 + 13,485.8 - 3725.1 - 1.986 \times 1800) \\ &\quad + (36.66)(0 + 12,956.3 - 3729.5 - 1.986 \times 1800) \\ &\quad - (1)(35,680 - 1.986 \times 537) - (9.75)(4.76)(-1.986 \times 537) \\ &= -946,870 \text{ Btu} \end{aligned}$$

or $Q_{out} = \mathbf{946,870 \text{ Btu}}$

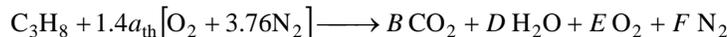


15-66 A high efficiency gas furnace burns gaseous propane C_3H_8 with 140 percent theoretical air. The volume flow rate of water condensed from the product gases is to be determined.

Assumptions 1 Combustion is complete. **2** The combustion products contain CO_2 , H_2O , O_2 , and N_2 only.

Properties The molar masses of C, H_2 , O_2 and air are 12 kg/kmol, 2 kg/kmol, 32 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

Analysis The reaction equation for 40% excess air (140% theoretical air) is



where a_{th} is the stoichiometric coefficient for air. We have automatically accounted for the 40% excess air by using the factor $1.4a_{th}$ instead of a_{th} for air. The coefficient a_{th} and other coefficients are to be determined from the mass balances

$$\text{Carbon balance:} \quad B = 3$$

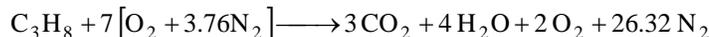
$$\text{Hydrogen balance:} \quad 2D = 8 \longrightarrow D = 4$$

$$\text{Oxygen balance:} \quad 2 \times 1.4a_{th} = 2B + D + 2E$$

$$0.4a_{th} = E$$

$$\text{Nitrogen balance:} \quad 1.4a_{th} \times 3.76 = F$$

Solving the above equations, we find the coefficients ($E = 2$, $F = 26.32$, and $a_{th} = 5$) and write the balanced reaction equation as



The partial pressure of water in the saturated product mixture at the dew point is

$$P_{v,prod} = P_{sat@40^\circ C} = 7.3851 \text{ kPa}$$

The vapor mole fraction is

$$y_v = \frac{P_{v,prod}}{P_{prod}} = \frac{7.3851 \text{ kPa}}{100 \text{ kPa}} = 0.07385$$

The kmoles of water condensed is determined from

$$y_v = \frac{N_{water}}{N_{total,product}} \longrightarrow 0.07385 = \frac{4 - N_w}{3 + 4 - N_w + 2 + 26.32} \longrightarrow N_w = 1.503 \text{ kmol}$$

The steady-flow energy balance is expressed as

$$\dot{N}_{fuel} H_R = \dot{Q}_{fuel} + \dot{N}_{fuel} H_P$$

$$\text{where} \quad \dot{Q}_{fuel} = \frac{\dot{Q}_{out}}{\eta_{furnace}} = \frac{31,650 \text{ kJ/h}}{0.96} = 32,969 \text{ kJ/h}$$

$$H_R = \bar{h}_{f, fuel@25^\circ C} + 7\bar{h}_{O_2@25^\circ C} + 26.32\bar{h}_{N_2@25^\circ C}$$

$$= (-103,847 \text{ kJ/kmol}) + 7(0) + 26.32(0) = -103,847 \text{ kJ/kmol}$$

$$H_P = 3\bar{h}_{CO_2@25^\circ C} + 4\bar{h}_{H_2O@25^\circ C} + 2\bar{h}_{O_2@25^\circ C} + 26.32\bar{h}_{N_2@25^\circ C} + N_w(\bar{h}_{f, H_2O(liq)}^o)$$

$$= 3(-393,520 \text{ kJ/kmol}) + 4(-241,820 \text{ kJ/kmol}) + 2(0) + 26.32(0) + 1.503(-285,830 \text{ kJ/kmol})$$

$$= -2.577 \times 10^6 \text{ kJ/kmol}$$

Substituting into the energy balance equation,

$$\dot{N}_{fuel} H_R = \dot{Q}_{fuel} + \dot{N}_{fuel} H_P$$

$$\dot{N}_{fuel}(-103,847 \text{ kJ/kmol}) = 32,969 \text{ kJ/h} + \dot{N}_{fuel}(-2.577 \times 10^6 \text{ kJ/kmol}) \longrightarrow \dot{N}_{fuel} = 0.01333 \text{ kmol/h}$$

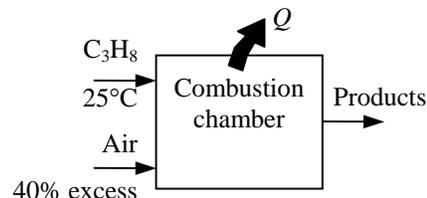
The molar and mass flow rates of the liquid water are

$$\dot{N}_w = N_w \dot{N}_{fuel} = (1.503 \text{ kmol/kmol fuel})(0.01333 \text{ kmol fuel/h}) = 0.02003 \text{ kmol/h}$$

$$\dot{m}_w = \dot{N}_w M_w = (0.02003 \text{ kmol/h})(18 \text{ kg/kmol}) = 0.3608 \text{ kg/h}$$

The volume flow rate of liquid water is

$$\dot{V}_w = (v_f @ 25^\circ C) \dot{m}_w = (0.001003 \text{ m}^3/\text{kg})(0.3608 \text{ kg/h}) = 0.0003619 \text{ m}^3/\text{h} = \mathbf{8.7 \text{ L/day}}$$



15-67 Liquid ethyl alcohol, C_2H_5OH (liq), is burned in a steady-flow combustion chamber with 40 percent excess air. The required volume flow rate of the liquid ethyl alcohol is to be determined.

Assumptions 1 Combustion is complete. 2 The combustion products contain CO_2 , H_2O , O_2 , and N_2 only.

Properties The molar masses of C, H_2 , O_2 and air are 12 kg/kmol, 2 kg/kmol, 32 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

Analysis The reaction equation for 40% excess air is



where a_{th} is the stoichiometric coefficient for air. We have automatically accounted for the 40% excess air by using the factor $1.4a_{th}$ instead of a_{th} for air. The coefficient a_{th} and other coefficients are to be determined from the mass balances

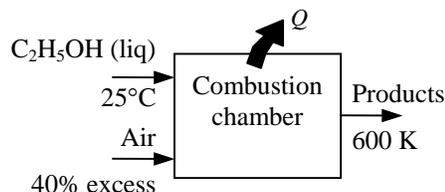
$$\text{Carbon balance:} \quad B = 2$$

$$\text{Hydrogen balance:} \quad 2D = 6 \longrightarrow D = 3$$

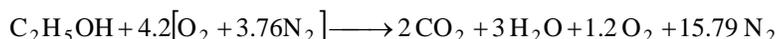
$$\text{Oxygen balance:} \quad 1 + 2 \times 1.4a_{th} = 2B + D + 2E$$

$$0.4a_{th} = E$$

$$\text{Nitrogen balance:} \quad 1.4a_{th} \times 3.76 = F$$



Solving the above equations, we find the coefficients ($E = 1.2$, $F = 15.79$, and $a_{th} = 3$) and write the balanced reaction equation as



The steady-flow energy balance is expressed as

$$\dot{N}_{fuel} H_R = \dot{Q}_{out} + \dot{N}_{fuel} H_P$$

where

$$\begin{aligned} H_R &= (\bar{h}_f^\circ - \bar{h}_{fg})_{fuel} + 4.2\bar{h}_{O_2@298.15K} + (4.2 \times 3.76)\bar{h}_{N_2@298.15K} \\ &= -235,310 \text{ kJ/kmol} - 42,340 \text{ kJ/kmol} + 4.2(-4.425 \text{ kJ/kmol}) + (4.2 \times 3.76)(-4.376 \text{ kJ/kmol}) \\ &= -277,650 \text{ kJ/kmol} \end{aligned}$$

$$\begin{aligned} H_P &= 2\bar{h}_{CO_2@600K} + 3\bar{h}_{H_2O@600K} + 1.2\bar{h}_{O_2@600K} + 15.79\bar{h}_{N_2@600K} \\ &= 2(-380,623 \text{ kJ/kmol}) + 3(-231,333 \text{ kJ/kmol}) + 1.2(9251 \text{ kJ/kmol}) + 15.79(8889 \text{ kJ/kmol}) \\ &= -1.304 \times 10^6 \text{ kJ/kmol} \end{aligned}$$

The enthalpies are obtained from EES except for the enthalpy of formation of the fuel, which is obtained in Table A-27 of the book. Substituting into the energy balance equation,

$$\dot{N}_{fuel} H_R = \dot{Q}_{out} + \dot{N}_{fuel} H_P$$

$$\dot{N}_{fuel} (-277,650 \text{ kJ/kmol}) = 2000 \text{ kJ/s} + \dot{N}_{fuel} (-1.304 \times 10^6 \text{ kJ/kmol}) \longrightarrow \dot{N}_{fuel} = 0.001949 \text{ kmol/s}$$

The fuel mass flow rate is

$$\dot{m}_{fuel} = \dot{N}_{fuel} M_{fuel} = (0.001949 \text{ kmol/s})(2 \times 12 + 6 \times 1 + 16) \text{ kg/kmol} = 0.08966 \text{ kg/s}$$

Then, the volume flow rate of the fuel is determined to be

$$\dot{V}_{fuel} = \frac{\dot{m}_{fuel}}{\rho_{fuel}} = \frac{0.08966 \text{ kg/s}}{790 \text{ kg/m}^3} \left(\frac{6000 \text{ L/min}}{1 \text{ m}^3/\text{s}} \right) = \mathbf{6.81 \text{ L/min}}$$