Problems

Working with Reaction Equations

13.1 A vessel contains a mixture of 60% O₂ and 40% CO on a mass basis. Determine the percent excess or percent deficiency of oxygen, as appropriate.

13.2 Estimate the amount of CO₂ produced, in lb, for every gallon of gasoline burned by an automobile. In a year, how much CO₂ would be produced, in lb, by a typical automobile in the U.S.?

13.3 One hundred kmol of propane (C₃H₈) together with 3572 kmol of air enter a furnace per unit of time. Carbon dioxide, carbon monoxide, and unburned fuel appear in the products of combustion exiting the furnace. Determine the percent excess or percent deficiency of air, whichever is appropriate.

13.4 Propane (C₃H₈) is burned with air. For each case, obtain the balanced reaction equation for complete combustion
   (a) with the theoretical amount of air.
   (b) with 20% excess air.
   (c) with 20% excess air, but only 90% of the propane being consumed in the reaction.

13.5 Methane (CH₄) burns completely with the stoichiometric amount of hydrogen peroxide (H₂O₂). Determine the balanced reaction equation.

13.6 A fuel mixture with the molar analysis 70% CH₄, 20% CO, 5% O₂, and 5% N₂, burns completely with 20% excess air. Determine
   (a) the balanced reaction equation.
   (b) the air–fuel ratio, both on a molar and mass basis.

13.7 A fuel mixture with the molar analysis 94.4% CH₄, 3.4% C₂H₆, 0.6% C₃H₈, 0.5% C₄H₁₀, 1.1% N₂ burns completely with 20% excess air in a reactor operating at steady state. If the molar flow rate of the fuel is 0.1 kmol/h, determine the molar flow rate of the air, in kmol/h.

13.8 A fuel mixture with the molar analysis of 20% CH₄, 40% H₂, 40% NH₃ burns completely with 150% of theoretical oxygen. Determine the balanced reaction equation.

13.9 Coal with the mass analysis 77.54% C, 4.28% H, 1.46% S, 7.72% O, 1.34% N, 7.66% noncombustible ash burns completely with 120% of theoretical air. Determine
   (a) the balanced reaction equation.
   (b) the amount of SO₂ produced, in kg per kg of coal.
13.10 A coal sample has a mass analysis of 77.39% carbon, 4.1% hydrogen (H₂), 5.31% oxygen (O₂), 1.62% nitrogen (N₂), 1.1% sulfur, and the rest is noncombustible ash. For complete combustion with 110% of the theoretical amount of air, determine the air–fuel ratio on a mass basis.

13.11 A sample of dried feedlot manure is being tested for use as a fuel. The mass analysis of the sample is 42.7% carbon, 5.5% hydrogen (H₂), 31.3% oxygen (O₂), 2.4% nitrogen (N₂), 0.3% sulfur, and 17.8% noncombustible ash. The sample is burned completely with 120% of theoretical air. Determine:
(a) the balanced reaction equation.
(b) the air–fuel ratio on a mass basis.

13.12 A sample of dried Appanoose County coal has a mass analysis of 71.1% carbon, 5.1% hydrogen (H₂), 9.0% oxygen (O₂), 1.4% nitrogen (N₂), 5.8% sulfur, and the rest noncombustible ash. For complete combustion with the theoretical amount of air, determine:
(a) the amount of SO₂ produced, in kg per kg of coal.
(b) the air–fuel ratio on a mass basis.

13.13 Dodecane (C₁₂H₂₅) burns completely with 150% of theoretical air. Determine:
(a) the air–fuel ratio on a molar and mass basis.
(b) the dew point temperature of the combustion products, in °C, when cooled at 1 atm.

13.14 Butane (C₄H₁₀) burns completely with 150% of theoretical air. If the combustion products are cooled at 1 atm to temperature T, plot the amount of water vapor condensed, in kmol per kmol of fuel, versus T ranging from 20 to 60°C.

13.15 Ethylene (C₂H₄) burns completely with air and the combustion products are cooled to temperature T at 1 atm. The air–fuel ratio on a mass basis is AF.
(a) Determine for AF = 15 and T = 70°F, the percent excess air and the amount of water vapor condensed, in lb per lbmol of fuel.
(b) Plot the amount of water vapor condensed, in lb per lbmol of fuel, versus T ranging from 70 to 100°F, for AF = 15, 20, 25, 30.

13.16 A gaseous fuel mixture with a molar analysis of 72% CH₄, 9% H₂, 14% N₂, 2% O₂, and 3% CO, burns completely with moist air to form gaseous products at 1 atm consisting of CO₂, H₂O, and N₂ only. If the dew point temperature of the products is 60°C, determine the amount of water vapor present in the combustion air, in kmol per kmol of fuel mixture.

13.17 The gas driven off when low-grade coal is burned with insufficient air for complete combustion is known as producer gas. A particular producer gas has the following volumetric analysis: 3.8% CH₄, 0.1% C₂H₂, 4.8% CO₂, 11.7% H₂, 0.6% O₂, 23.2% CO, and the remainder N₂. Determine, for complete combustion with the theoretical amount of air:
(a) the molar analysis of the dry products of combustion.
(b) the amount of water vapor condensed, in lbmol/lbmol of producer gas, if the products are cooled to 70°F at a constant pressure of 1 atm.

13.18 Propane (C₃H₈) enters a combustion chamber and burns completely with 140% of theoretical air entering at 40°C, 1 atm, 75% relative humidity. Obtain the balanced reaction equation, and determine the dew point temperature of the products, in °C.

13.19 Butane (C₄H₁₀) enters a combustion chamber and burns completely with 150% of theoretical air entering at 68°F, 1 atm, 75% relative humidity. Determine:
(a) the balanced reaction equation.
(b) the amount of water condensed, in lbmol per lbmol of fuel, if the combustion products are cooled to 68°F at 1 atm.

13.20 Methane (CH₄) enters a furnace and burns completely with 150% of theoretical air entering at 25°C, 94.5 kPa, 75% relative humidity. Determine:
(a) the balanced reaction equation.
(b) the dew point temperature of the combustion products, in °C, at 94.5 kPa.

13.21 Pentane (C₅H₁₂) burns completely with the theoretical amount of air at 75°F, 1 atm, 75% relative humidity. Determine:
(a) the balanced reaction equation.
(b) the dew point temperature of the combustion products at 1 atm.
(c) the amount of water condensed, in lbmol per lbmol of fuel, if the combustion products are cooled to 75°F at 1 atm.

13.22 A liquid fuel mixture that is 40% octane (C₈H₁₈) and 60% decane (C₁₀H₂₂) by mass is burned completely with 10% excess air at 25°C, 1 atm, 80% relative humidity.
(a) Determine the equivalent hydrocarbon composition, CₓHᵧ, of a fuel that would have the same carbon-hydrogen ratio on a mass basis as the fuel mixture.
(b) If the combustion products are cooled to 25°C at a pressure of 1 atm, determine the amount of water vapor that condenses, in kg per kg of fuel mixture.

13.23 Hydrogen (H₂) enters a combustion chamber with a mass flow rate of 2 kg/h and burns with air entering at 30°C, 1 atm with a volumetric flow rate of 120 m³/h. Determine the percent of theoretical air used.

13.24 Carbon burns with 80% theoretical air yielding CO₂, CO, and N₂ only. Determine:
(a) the balanced reaction equation.
(b) the air–fuel ratio on a mass basis.
(c) the analysis of the products on a molar basis.

13.25 Propane (C₃H₈) reacts with 80% of theoretical air to form products including CO₂, CO, H₂O, and N₂ only. Determine...
(a) the balanced reaction equation.
(b) the air–fuel ratio on a mass basis.
(c) the analysis of the products on a dry molar basis.

13.26 Dodecane \( (C_{12}H_{26}) \) enters an engine and burns with air to give products with the dry molar analysis of \( CO_2 \), 12.1%; \( CO \), 3.4%; \( O_2 \), 0.5%; \( H_2 \), 1.5%; \( N_2 \), 82.5%. Determine the air–fuel ratio on a molar basis.

13.27 The components of the exhaust gas of a spark-ignition engine using a fuel mixture represented as \( C_8H_{18} \) have a dry molar analysis of 8.7% \( CO_2 \), 8.9% \( CO \), 0.3% \( O_2 \), 3.7% \( H_2 \), 0.3% \( CH_4 \), and 78.1% \( N_2 \). Determine the equivalence ratio.

13.28 Decane \( (C_{10}H_{22}) \) burns with 95% of theoretical air, producing a gaseous mixture of \( CO_2 \), \( CO \), \( H_2O \), and \( N_2 \). Determine
(a) the air–fuel ratio on a molar basis.
(b) the analysis of the products on a dry molar basis.

13.29 Butane \( (C_4H_{10}) \) burns with air, giving products having the dry molar analysis 11.0% \( CO_2 \), 1.0% \( CO \), 3.5% \( O_2 \), 84.5% \( N_2 \). Determine
(a) the percent theoretical air.
(b) the dew point temperature of the combustion products, in °C, at 1 bar.

13.30 A natural gas with the volumetric analysis 97.3% \( CH_4 \), 2.3% \( CO_2 \), 0.4% \( N_2 \) is burned with air in a furnace to give products having a dry molar analysis of 9.20% \( CO_2 \), 3.84% \( O_2 \), 0.64% \( CO \), and the remainder \( N_2 \). Determine
(a) the percent theoretical air
(b) the dew point temperature, in °F, of the combustion products at 1 atm.

13.31 A fuel oil having an analysis on a mass basis of 85.7% \( C \), 14.2% \( H \), 0.1% inert matter burns with air to give products with a dry molar analysis of 12.29% \( CO_2 \); 3.76% \( O_2 \); 83.95% \( N_2 \). Determine the air–fuel ratio on a mass basis.

13.32 Liquid methanol \( (CH_3OH) \) burns with air. The product gas is analyzed and the laboratory report gives only the following percentages on a dry molar basis: 7.1% \( CO_2 \), 2.4% \( CO \), 0.84% \( CH_4 \). Assuming the remaining components consist of \( O_2 \) and \( N_2 \), determine
(a) the percentages of \( O_2 \) and \( N_2 \) in the dry molar analysis.
(b) the percent excess air.

13.33 A fuel oil with the mass analysis 87% \( C \), 11% \( H \), 1.4% \( S \), 0.6% inert matter burns with 120% of theoretical air. The hydrogen and sulfur are completely oxidized, but 95% of the carbon is oxidized to \( CO_2 \) and the remainder to \( CO \).
(a) Determine the balanced reaction equation.
(b) For the \( CO \) and \( SO_2 \), determine the amount, in kmol per 10^9 kmol of combustion products (that is, the amount in parts per million).

13.34 Pentane \( (C_5H_{12}) \) burns with air so that a fraction \( x \) of the carbon is converted to \( CO_2 \). The remaining carbon appears as \( CO \). There is no free \( O_2 \) in the products. Develop plots of the air–fuel ratio and the percent of theoretical air versus \( x \), for \( x \) ranging from zero to unity.

13.35 For each of the following mixtures, determine the equivalence ratio and indicate if the mixture is lean or rich:
(a) 1 lbmol of methane \( (CH_4) \) and 8 lbmol of air.
(b) 1 kg of ethane \( (C_2H_6) \) and 17.2 kg of air.

13.36 Octane \( (C_{10}H_{22}) \) enters an engine and burns with air to give products with the dry molar analysis of \( CO_2 \), 10.5%; \( CO \), 5.8%; \( CH_4 \), 0.9%; \( H_2 \), 2.6%; \( O_2 \), 0.3%; \( N_2 \), 79.9%. Determine the equivalence ratio.

13.37 Methane \( (CH_4) \) burns with air to form products consisting of \( CO_2 \), \( CO \), \( H_2O \), and \( N_2 \) only. If the equivalence ratio is 1.25, determine the balanced reaction equation.

Applying the First Law to Reacting Systems

13.38 Ethane \( (C_2H_6) \) at 77°F, 1 atm enters a combustion chamber operating at steady state and burns completely with the theoretical amount of air entering at the same conditions. If the products exit at 150°F, 1 atm, determine the rate of heat transfer from the combustion chamber, in Btu per lbmol of fuel. Kinetic and potential energy effects are negligible.

13.39 Propane \( (C_3H_8) \) at 25°C, 1 atm enters a combustion chamber operating at steady state and burns completely with the theoretical amount of air entering at the same conditions. If the products exit at 25°C, 1 atm, determine the rate of heat transfer from the combustion chamber, in kJ per kmol of fuel. Kinetic and potential energy effects are negligible.

13.40 Methane \( (CH_4) \) at 25°C, 1 atm enters a steam generator operating at steady state. The methane burns completely with 140% of theoretical air entering at 127°C, 1 atm. Products of combustion exit at 427°C, 1 atm. In a separate stream, saturated liquid water enters at 8 MPa and exits as superheated vapor at 480°C with a negligible pressure drop. If the vapor mass flow rate is \( 3.7 \times 10^6 \) kg/h, determine the volumetric flow rate of the methane, in m³/h.

13.41 Liquid ethanol \( (C_2H_5OH) \) at 25°C, 1 atm enters a combustion chamber operating at steady state and burns with air entering at 227°C, 1 atm. The fuel flow rate is 25 kg/s and the equivalence ratio is 1.2. Heat transfer from the combustion chamber to the surroundings is at a rate of \( 3.75 \times 10^6 \) kJ/s. Products of combustion, consisting of \( CO_2 \), \( CO \), \( H_2O \) (g), and \( N_2 \) exist. Ignoring kinetic and potential energy effects, determine
(a) the exit temperature, in K.
(b) the air–fuel ratio on a mass basis.

13.42 Benzene gas \( (C_6H_6) \) at 25°C, 1 atm enters a combustion chamber operating at steady state and burns with 95% theoretical air entering at 25°C, 1 atm. The combustion products exit at 1000 K and include only \( CO_2 \), \( CO \), \( H_2O \), and \( N_2 \). Determine the mass flow rate of the fuel, in kg/s, to provide heat transfer at a rate of 1000 kW.
13.43 The energy required to vaporize the working fluid passing through the boiler of a simple vapor power plant is provided by the complete combustion of methane with 110% of theoretical air. The fuel and air enter in separate streams at 25°C, 1 atm. Products of combustion exit the stack at 150°C, 1 atm. Plot the mass flow rate of fuel required, in kg/h per MW of power developed by the plant versus the plant thermal efficiency, η. Consider η in the range 30–40%. Kinetic and potential energy effects are negligible.

13.44 Gaseous octane (C₈H₁₀) at 25°C, enters the combustor of a simple open gas turbine power plant and burns completely with 400% of theoretical air entering the compressor at 25°C, 1 atm. Products of combustion exit the turbine at 627°C, 1 atm. If the rate of heat transfer from the gas turbine is estimated as 15% of the net power developed, determine the molar flow rate of the fuel, in kmol/h, for a net power output of 1 MW. Kinetic and potential energy effects are negligible.

13.45 Octane gas (C₈H₁₀) at 25°C enters a jet engine and burn with 300% of theoretical air entering at 25°C, 1 atm with a volumetric flow rate of 42 m³/s. Products of combustion exit at 990 K, 1 atm. If the fuel and air enter with negligible velocities, determine the thrust produced by the engine in kN.

13.46 Figure P13.46 provides data for a boiler and air preheater operating at steady state. Methane (CH₄) entering the boiler at 25°C, 1 atm is burned completely with 170% of theoretical air. Ignoring stray heat transfer and kinetic and potential energy effects, determine the temperature, in °C, of the combustion air entering the boiler from the preheater.

![Diagram of boiler and air preheater]

13.47 A rigid tank initially contains 16.04 lb of CH₄ and 96 lb of O₂ at 77°F, 1 atm. After complete combustion, the pressure in the tank is 3.352 atm. Determine the heat transfer, in Btu.

13.48 A closed rigid vessel initially contains a gaseous mixture at 25°C, 1 atm with the molar analysis of 25% ethylene (C₂H₄), 75% oxygen (O₂). The mixture burns completely and the products are cooled to 500 K. Determine the heat transfer between the vessel and its surroundings, in kJ per kmol of fuel present initially, and the final pressure, in atm.

13.49 A closed, rigid vessel initially contains a gaseous mixture of 1 kmol of benzene (C₆H₆) and 200% of theoretical air at 25°C, 1 atm. If the mixture burns completely, determine the heat transfer from the vessel, in kJ, and the final pressure, in atm, for a final temperature of 700 K.

13.50 Determine the enthalpy of combustion for gaseous butane (C₄H₁₀), in kJ per kmol of fuel and kJ per kg of fuel, at 25°C, 1 atm, assuming

(a) water vapor in the products.
(b) liquid water in the products.

13.51 Plot the enthalpy of combustion for gaseous propane (C₃H₈), in Btu per lbmol of fuel, at 1 atm versus temperature in the interval 77 to 500°F. Assume water vapor in the products. For propane, let cᵥ = 0.41 Btu/lb·°R.

13.52 Plot the enthalpy of combustion for gaseous methane (CH₄), in Btu per lbmol of fuel, at 1 atm versus temperature in the interval from 537 to 1800°F. Assume water vapor in the products. For methane, let cᵥ = 4.52 + 7.37(71000) Btu/lb·°R, where T is in °R.

13.53 For the producer gas of Prob. 13.17, determine the enthalpy of combustion, in Btu per lbmol of mixture, at 77°F, 1 atm, assuming water vapor in the products.

13.54 Determine the higher heating value, in kJ per kmol of fuel and in kJ per kg of fuel, at 25°C, 1 atm for

(a) liquid octane (C₈H₁₈).
(b) gaseous hydrogen (H₂).
(c) liquid methanol (CH₃OH).
(d) gaseous butane (C₄H₁₀).

Compare with the values listed in Table A-25.

13.55 For a natural gas with a molar analysis of 86.5% CH₄, 8% C₂H₆, 2% C₃H₈, 3.5% N₂, determine the lower heating value, in kJ per kmol of fuel and in kJ per kg of fuel, at 25°C, 1 atm.

13.56 Liquid octane (C₈H₁₈) at 25°C, 1 atm enters an insulated reactor operating at steady state and burns with 90% of theoretical air at 25°C, 1 atm to form products consisting of CO₂, CO, H₂O, and N₂ only. Determine the temperature of the exiting products, in K. Compare with the results of Example 13.8 and comment.

13.57 For each of the following fuels, plot the adiabatic flame temperature, in K, versus percent excess air for complete combustion in a combustor operating at steady state. The reactants enter at 25°C, 1 atm.

(a) carbon.
(b) hydrogen (H₂).
(c) liquid octane (C₈H₁₈).

13.58 Propane gas (C₃H₈) at 25°C, 1 atm enters an insulated reactor operating at steady state and burns completely with air entering at 25°C, 1 atm. Plot the adiabatic flame temperature versus percent of theoretical air ranging from
100 to 400%. Why does the adiabatic flame temperature vary with increasing combustion air?

13.59 Hydrogen (H₂) at 77°F, 1 atm enters an insulated reactor operating at steady state and burns completely with x% of theoretical air entering at 77°F, 1 atm. Plot the adiabatic flame temperature for x ranging from 100 to 400%.

13.60 Methane gas (CH₄) at 25°C, 1 atm enters an insulated reactor operating at steady state and burns completely with x% of theoretical air entering at 25°C, 1 atm. Plot the adiabatic flame temperature for x ranging from 100 to 400%.

13.61 Methane (CH₄) at 25°C, 1 atm enters an insulated reactor operating at steady state and burns completely with the theoretical amount of air entering at 25°C, 1 atm. The products contain CO₂, H₂O, O₂, and N₂, and exit at 2260 K. Determine the fractions of the entering carbon in the fuel that burn to CO₂ and CO, respectively.

13.62 Propane gas (C₃H₈) at 77°F, 1 atm enters an insulated reactor operating at steady state and burns completely with air entering at 77°F, 1 atm. Determine the percent of theoretical air if the combustion products exit at
   (a) 1140°F.
   (b) 2240°F.
Neglect kinetic and potential energy effects.

13.63 Liquid methanol (CH₃OH) at 25°C, 1 atm enters an insulated reactor operating at steady state and burns completely with air entering at 100°C, 1 atm. If the combustion products exit at 1256°C, determine the percent excess air used. Neglect kinetic and potential energy effects.

13.64 Methane (CH₄) at 77°F enters the combustor of a gas turbine power plant operating at steady state and burns completely with air entering at 400°F. The temperature of the products of combustion flowing from the combustor to the turbine depends on the percent excess air for combustion. Plot the percent excess air versus combustion product temperatures ranging from 1400 to 1800°F. There is no significant heat transfer between the combustor and its surroundings, and kinetic and potential energy effects can be ignored.

13.65 Air enters the compressor of a simple gas turbine power plant at 70°F, 1 atm, is compressed adiabatically to 40 lbm/in², and then enters the combustion chamber where it burns completely with propane gas (C₃H₈) entering at 77°F, 40 lbm/in² and a molar flow rate of 1.7 lbmol/h. The combustion products at 1340°F, 40 lbm/in² enter the turbine and expand adiabatically to a pressure of 1 atm. The isentropic compressor efficiency is 85.3% and the isentropic turbine efficiency is 90%. Determine at steady state
   (a) the percent of theoretical air required.
   (b) the net power developed, in horsepower.

13.66 A mixture of gaseous octane (C₈H₁₈) and 200% of theoretical air, initially at 25°C, 1 atm, reacts completely in a rigid vessel.

(a) If the vessel were well-insulated, determine the temperature, in °C, and the pressure, in atm, of the combustion products.
(b) If the combustion products were cooled at constant volume to 25°C, determine the final pressure, in atm, and the heat transfer, in kJ per kmol of fuel.

13.67 A mixture of methane (CH₄) and 200% of theoretical air, initially at 77°F, 1 atm, reacts completely in an insulated vessel. Determine the temperature, in °F, of the combustion products if the reaction occurs
   (a) at constant volume.
   (b) at constant pressure in a piston-cylinder assembly.

13.68 A 5 × 10⁻³ kg sample of liquid benzene (C₆H₆) together with 20% excess air, initially at 25°C and 1 atm, reacts completely in a rigid, insulated vessel. Determine the temperature, in °C, and the pressure, in atm, of the combustion products.

Applying the Second Law to Reacting Systems

13.69 Carbon monoxide (CO) at 25°C, 1 atm enters an insulated reactor operating at steady state and reacts completely with the theoretical amount of air entering in a separate stream at 25°C, 1 atm. The products of combustion exit as a mixture at 1 atm. For the reactor, determine the rate of entropy production, in kJ/K per kmol of CO entering. Neglect kinetic and potential energy effects.

13.70 Methane (CH₄) at 77°F, 1 atm enters an insulated reactor operating at steady state and burns completely with air entering in a separate stream at 77°F, 1 atm. The products of combustion exit as a mixture at 1 atm. For the reactor, determine the rate of entropy production, in kJ/K per kmol of methane entering, for combustion with
   (a) the theoretical amount of air,
   (b) 200% of theoretical air.
Neglect kinetic and potential energy effects.

13.71 Carbon monoxide (CO) reacts with water vapor in an insulated reactor operating at steady state to form hydrogen (H₂) and carbon dioxide (CO₂). The products exit as a mixture at 1 atm. For the reactor, determine the rate of entropy production, in kJ/K per kmol of carbon monoxide entering. Neglect kinetic and potential energy effects. Consider two cases:
   (a) the carbon monoxide and water vapor enter the reactor as separate streams, each at 400 K, 1 atm.
   (b) the carbon monoxide and water vapor enter the reactor as a mixture at 400 K, 1 atm.

Explain why the answers in parts (a) and (b) differ.

13.72 A gaseous mixture of butane (C₄H₁₀) and 80% excess air at 25°C, 3 atm enters a reactor. Complete combustion occurs, and the products exit as a mixture at 1200 K, 3 atm. Coolant enters an outer jacket as a saturated liquid and saturated vapor exits at essentially the same pressure.