ME 440
Aerospace Engineering Fundamentals

Combustion Examples

<u>Example: Combustion of Butane with Specified Air to Fuel Ratio</u>

Butane is burned with air with 130% theoretical air. Balance the chemical reaction equation and determine the air to fuel ratio of the combustion process.

Solution:

We begin by writing our unbalanced theoretical chemical reaction equation for butane.

$$C_4H_{10} + a(TA)O_2 + a(TA)(3.76)N_2 \rightarrow bCO_2 + dH_2O + a(TA-1)O_2 + a(TA)(3.76)N_2$$

Now balancing we find

C: 4 = b

H: 10 = 2d, d = 5

O: 2a = 2b + d, a = 6.5

Now writing our general combustion equation for butane at 130% theoretical air

$$C_4H_{10} + 8.45O_2 + 31.77N_2$$
$$\rightarrow 4CO_2 + 5H_2O + 1.95O_2 + 31.77N_2$$

Our air to fuel ratio is given by

$$AF_{mole} = \frac{8.45 + 31.77}{1} = 40.22$$

Example: Heat Transfer for Octane Combustion

Consider the combustion of octane with 400% theoretical air. If the octane (liq) and air enter the combustion chamber at 25°C and 100 kPa and the products exit at 1000K and 100 kPa, determine the heat transfer.

Solution:

We begin with our unbalanced theoretical combustion equation for octane.

$$C_8H_{18} + aO_2 \rightarrow bCO_2 + dH_2O$$

Now balancing we find

C: 8 = b

H: 18 = 2d, d =9

O: 2a = 2b + d, a = 12.5

Now writing our general combustion equation for octane in air

$$C_8H_{18} + 12.5(TA)O_2 + 12.5(TA)(3.76)N_2$$
$$\rightarrow 8CO_2 + 9H_2O + 12.5(TA-1)O_2 + 47(TA)N_2$$

Then with TA = 400, we have

$$C_8H_{18} + 50O_2 + 188N_2$$
$$\rightarrow 8CO_2 + 9H_2O + 37.5O_2 + 188N_2$$

Now writing our first law,

$$H_R + Q = H_P$$

Solving for Q gives

$$Q = H_P - H_R$$

Writing our enthalpies (assuming that at 1000 K all our water will be in vapor form)

$$H_P = 8[h]_{CO2} + 9[h]_{H2O(v)} + 37.5[h]_{O2,P} + 188[h]_{N2,P}$$
$$H_R = [h]_{C8H18(l)} + 50[h]_{O2,R} + 188[h]_{N2,R}$$

Evaluating our h's (recall that $h = h_f + c_P(T\text{-}298)$)

$$h_{C8H18} = -249{,}910 \text{ kJ/kgmole}$$
$$h_{O2,R} = 0 \text{ kJ/kgmole}$$
$$h_{N2,R} = 0 \text{ kJ/kgmole}$$
$$h_{H2O(v)} = -241{,}827 + (33.73)(1000\text{-}298) = -218{,}148 \text{ kJ/kgmole}$$
$$h_{CO2} = -393{,}520 + (37.05)(1000\text{-}298) = -367{,}514 \text{ kJ/kgmole}$$
$$h_{O2,R} = (29.49)(1000\text{-}298) = 20{,}702 \text{ kJ/kgmole}$$
$$h_{N2,R} = (29.18)(1000\text{-}298) = 20{,}483 \text{ kJ/kgmole}$$

Now substituting

$$H_P = 8[-367{,}514] + 9[-218{,}148] + 37.5[20{,}702]$$
$$+ 188[20{,}483] = -276{,}284 \text{ kJ/kgmole}$$
$$H_R = -249{,}910 \text{ kJ/kgmole}$$

Calculating we have

$$Q = -276{,}284 - (-249{,}910) = -26{,}332 \text{ kJ/kmole of fuel}$$

Example: Adiabatic Flame Temperature for Propane Combustion

Consider the combustion of propane with 250% theoretical air. What is the maximum temperature this process can achieve? Assume that the reactants enter the combustion chamber at 25°C and 100 kPa.

Solution:

We must begin by writing our general combustion equation for propane.

$$C_3H_8 + a(TA)O_2 + a(TA)(3.76)N_2$$
$$\rightarrow bCO_2 + dH_2O + a(TA\text{-}1)O_2 + a(3.76)(TA)N_2$$

Balancing

C: 3=b

H: 8=2d, d=4

O: 2a=2b+d, a=5

Now with 250% theoretical air (TA=2.5), we have

$$C_3H_8 + 12.5O_2 + 47N_2 \rightarrow 3CO_2 + 4H_2O + 7.5O_2 + 47N_2$$

Now writing our first law,

$$H_R + Q = H_P$$

But we are seeking the maximum temperature, so that Q = 0 and

$$H_R = H_P$$

Now expanding our enthalpies

$$[h_f + c_P(T_R-298)]_{C3H8} + 12.5c_{P,O2}(T_R-298) + 47c_{P,N2}(T_R-298)$$
$$= 3[h_f + c_P(T_P-298)]_{CO2} + 4[h_f + c_P(T_P-298)]_{H2O} + 7.5c_{P,O2}(T_P-298) + 47c_{P,N2}(T_P-298)$$

Solving for T_p

$$T_p = 298 + \{h_{f,C3H8} - 3h_{f,CO2} - 4h_{f,H2O}\}/\{3c_{P,CO2} + 4c_{P,H2O} + 7.5c_{P,O2} + 47c_{P,N2}\}$$

Calculating we find an adiabatic flame temperature of 1410 K.

Example: Turbojet Specific Fuel Consumption

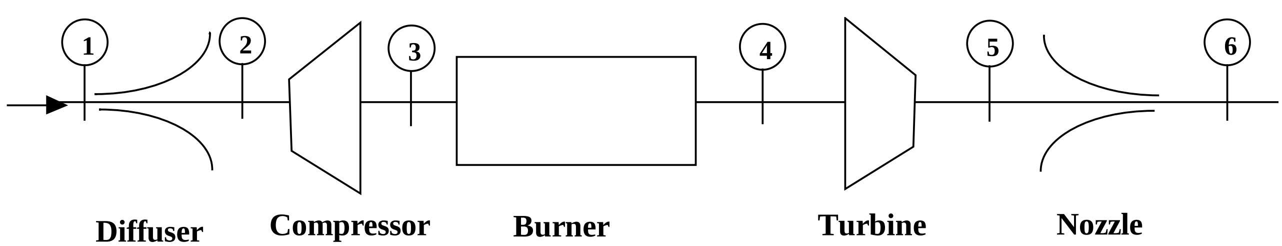
Consider the ideal turbojet example worked in our propulsion unit. For kerosene as the fuel, determine the specific fuel consumption for the engine. What is the fuel consumption rate for an engine of thrust 6000 Nt?

Solution:

Using the table of properties from the previous example we have

Node	T(K)	P(kPa)	V (m/s)
1	269	69.2	300
2	**314**	**118.6**	0
3	**622**	**1300**	0
4	1800	1300	0
5	**1492**	**673.9**	0
6	**779**	69.2	**1197**

The layout of this engine is shown below.



The specific fuel consumption is defined as

$$SFC = \frac{\dot{m}_{fuel}}{F_t} = \frac{(FA)\dot{m}_{air}}{F_t}\ \frac{(FA)}{f_t}$$

Previously we found

$$f_t = 897 \text{ N} \cdot \text{s/kg}$$

So that we need to find the fuel to air ratio on a mass basis for our burner. With our fuel as kerosene, we can write our chemical reaction equation as

$$C_{14}H_{27} + a(TA)O_2 + a(TA)(3.76)N_2$$
$$\rightarrow bCO_2 + dH_2O + a(TA\text{-}1)O_2 + a(3.76)(TA)N_2$$

Carrying out the balancing

C: 14 = b

H: 27 = 2d, d = 13.5

O: 2a = 2b+d , a = 20.75

Then our chemical reaction equation becomes

$$C_{14}H_{27} + (20.75)(TA)O_2 + (TA)(78)N_2$$
$$\rightarrow 14CO_2 + (13.5)H_2O + (20.75)(TA\text{-}1)O_2 + (78)(TA)N_2$$

Our TA will come form our conservation of energy equation. We assume that the burner is adiabatic, so that

Q = 0

and

$$H_R = H_P$$

We can then write

$$h_{f,C14H27} + c_{P,C14H27}(T_{fuel}-298) + (20.75)(TA)c_{P,O2}(T_3-298) + (TA)(78)c_{P,c14H27}(T_3-298)$$
$$= 14\{h_{f,CO2} + c_{P,CO2}(T_4-298)\} + 13.5\{h_{f,H2O} + c_{P,H2O}(T_4-298)\}$$
$$+ (20.75)(TA-1)c_{P,O2}(T_4-298) + (TA)(78)c_{P,c14H27}(T_3-298)$$

Since it was not specified, we will assume that our fuel will enter the burner at 298 K. Then solving for TA we have

$$TA = [14\{h_{f,CO2} + c_{P,CO2}(T_4 - 298)\} + 13.5\{h_{f,H2O} + c_{P,H2O}(T_4 - 298)\} - h_{f,C14H27}$$
$$- (20.75)c_{P,O2}(T_4 - 298)]$$
$$\div[(20.75)c_{P,O2}(T_3 - 298) + (78)c_{P,N2}(T_3 - 298) - (20.75)c_{P,O2}(T_4 - 298)$$
$$- (78)c_{P,N2}(T_4 - 298)]$$

Calculating we find

TA = 2.31

Our fuel to air ratio is given by

$$(FA)_{mass} = \frac{(1\text{mole})(MW_{C14H27})}{(20.75)(4.76)(TA)(MW_{air})} = \frac{(1\text{mole})(195)}{(20.75)(4.76)(2.31)(28.8)} = 0.03$$

Then

$$SFC = \frac{0.03}{897} = 3.31 \times 10^{-5} \text{ (kg/s)/Nt}$$

The required mass flow rate of fuel to produce 6000 Nt of thrust is given by

$$\dot{m}_{fuel} = (FA)_{mass}\,\dot{m}_{air}$$

where

$$\dot{m}_{air} = \frac{F_t}{f_t} = \frac{6000}{897} = 6.69 kg/s$$

Then

$$\dot{m}_{fuel} = (0.03)(6.69) = 0.2 kg/s$$