Gas Turbine Analysis

ME 475 - Thermo-Fluids Lab

March 2, 2016

For the property calculations in this lab, we will use the HOT Thermochemical calculator. This property calculator is used because it can handle gas mixtures and high temperatures easily. Its use is different than cooprops, so the syntax will be described here:

You will use the files located in

P:\me_drive\ME 475 Thermal Properties\HOT Thermochemical Calculator.

There is an example file included in the directory. You can just copy the files into your working directory.

```
addpath('HOT_R2','HOT_R2/HOT','HOT_R2/utility')
```

The first step is to load the thermochemical data into MATLAB (this need only be executed ONCE per MATLAB session).

```
data = janload('nasa.fit','sort','species')
```

Then, a mixture of gases must be defined. The gas types are defined using strings, and their relative amounts are defined using their mass fractions. The mass fractions do not need to be scaled so that they sum to one.

```
air = {'N2', 'O2'}
m_air = [3.29; 1]
```

Once we have defined the mixture we can then make property calls. The property calls require the thermochemical data and the definitions of the mixture.

enthalpy(h_0) = `enthalpy(data, air, m_air,` T_0`)`

entropy(s_0) = `entropy(data, air, m_air,` T_0, P_0`)`

specific heat ratio(γ) = `spratio(data, air, m_air, T)`

gas constant(R) = `igconstant(data, air, m_air)`

Temperature must be provided in Kelvin and Pressure in Pascals. Since the thermochemical calculator only deals with ideal gases, some of the property calls only require temperature and not two independent thermodynamic variables. If you look closely, all of your enthalpies will be negative (surprising!). True enthalpies include chemical energy (energy stored in the bonds of the molecule). When you break apart a molecule, you release this chemical energy and it is available to heat the flow (combustion). So in order to determine the sensible enthalpy (the part of the enthalpy which does not include the chemical energy), we need to subtract out the bond energy. The chemical energy is defined as the enthalpy of the molecule at zero temperature (when all the potential energy of the system is only stored in the chemical bonds). Thus, the true (sensible) enthalpies for gases are determined by

```
enthalpy(data, air, m_air, T) - enthalpy(data, air, m_air, 0)
```

We do not need to do the same thing for entropies because at the most basic level entropy comes from molecular motion. At zero temperature, there is no entropy since molecular motion has stopped. Now we can describe how to calculate quantities of interest through the engine cycle.

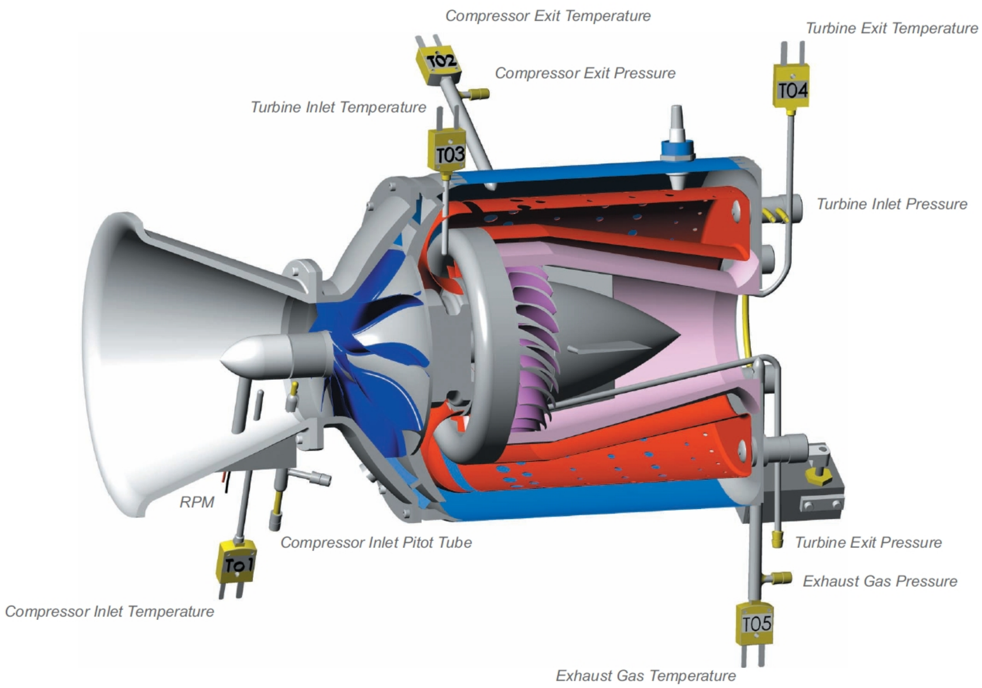

Figure 1: SR-30 Minilab engine cutaway showing measurement locations

1 Relationship between Pressure, Temperature and Velocity

As in incompressible sub-sonic flow, we can use pressure to calculate the fluid velocity. However, in the case of the gas turbine we'll often use pitot tubes which measure stagnation (total) pressures. for this reason, you'll need to become familiar with the differences between static and stagnation properties before proceeding. You can find this explanation in your textbook in the first section of the Compressible Flow chapter.

In the gas turbine, the flow will likely moving faster than M=0.1 so Bernoulli's equation is no longer valid. If measuring the inlet velocity (state 1 as shown in Figure 1), you can use the room pressure as the stagnation pressure P_0 since the air in the inlet was accelerated from atmospheric conditions like the wind tunnel. By measuring the static pressure we can use the ratio of static and stagnation pressures (P_o/P) to find the local Mach number.

$$M_inlet = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_{0_1}}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{1}$$

From the Mach number we can determine the local static temperature using the measured local stagnation temperature (T_{0_1}).

$$T_1 = \frac{T_{0_1}}{1+\frac{\gamma-1}{2}M^2} \tag{2}$$

Using the local temperature, we can compute the local speed of sound (using the specific heat ratio, γ, and gas constant, R, as found from the thermochemical calculator) and the flow velocity. From those, we can find the mass flow rate through the engine.

$$a_1 = \sqrt{\gamma R T_1} \tag{3}$$
$$V_1 = M_1 \times a_1 \tag{4}$$
$$\dot{m}_{\text{air}} = \rho_1 V_1 A_1 \tag{5}$$

All of these relationships are derived from the expressions you used in thermodynamics for an ideal gas undergoing an isentropic process assuming the specific heats are constant over that process.

2 Component Efficiencies

Each individual component has a thermodynamic efficiency which can be determined from the *stagnation properties*. The isentropic states can be computed using the `process` command in the themochemical calculator. The syntax for a isentropic process determined by a new pressure would be:

state = process(data, 'species', air, 'mass', m_air, 'P', P_0, 's',s_0)
T_0 = state.T
h_{0_s} = enthalpy(data, air, m_air, T_0) - enthalpy(data, air, m_air, 0)

3 Cycle Performance Characteristics

Several performance characteristics are used to determine the overall efficiency and performance of the gas turbine engine:

Specific Thrust

$$T_S = \frac{\text{Thrust}}{\dot{m}_{\text{air}}} \tag{6}$$

Thrust Specific Fuel Consumption

$$\text{TSFC} = \frac{\dot{m}_{\text{fuel}}}{\text{Thrust}} \tag{7}$$

Cycle Efficiency

$$\eta_{\text{cyc}} = 1 - \frac{h_{0_5} - h_{0_1}}{h_{0_3} - h_{0_2}} \tag{8}$$

Power Match (between the compressor and turbine)

$$\text{PM} = \frac{(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}})(h_{0_3} - h_{0_4})}{\dot{m}_{\text{air}}(h_{0_2} - h_{0_1})} \tag{9}$$

where PM should be 1 for an ideal compressor/turbine combination

Propulsive Efficiency

$$\eta_{\text{prop}} = \frac{\text{Thrust} \times V_1}{(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}})(h_{0_5} - h_5) - \dot{m}_{\text{air}}(h_{0_1} - h_1)} \tag{10}$$

Combustor Efficiency

$$\eta_{\text{comb}} = \frac{(1+f)h_{0_3} - h_{0_2}}{fQ_{\text{Jet A}}} \tag{11}$$

where $Q_{\text{Jet A}}$ is the heat of combustion or lower heating value of Jet A (JP-8) fuel and f is the air/fuel ratio defined by $f = \frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air}}}$.

4 Theoretical Gas Turbine Performance

Gas turbine performance can be estimated theoretically using control volume analysis to determine the ideal thrust achievable for a given velocity increase and air/fuel ratio.

Theoretical Thrust

$$T_{\text{theory}} = \dot{m}_{\text{air}}(1+f)V_5 - \dot{m}_{\text{air}}V_1 \tag{12}$$

Theoretical Specific Thrust

$$T_{S_{\text{theory}}} = (1+f)V_5 - V_1 \tag{13}$$

Theoretical Thrust Specific Fuel Consumption

$$\text{TSFC}_{\text{theory}} = \frac{f}{(1+f)V_5 - V_1} \tag{14}$$