Turbojet Overview

• Development of the turbojet is credited to 2 independent sources in the 1930's
  – Frank Whittle
  – Hans-Joachim Pabst von Ohain

Turbojet Overview

• vs. ramjet, basic layout adds
  1. **compressor(s)**
     • not relying on ram compression to achieve high pressure (and thus high $\eta_T$)
  2. **turbine(s)**
     • needed to run compressor(s)
     • connected by shaft(s)
  3. **afterburner/augmentor/reheater**
     • produces “peak” thrust
     • resembles ramjet burner
Comments on Turbojet Operation

- Unlike ramjets, compressors allow turbojet to operate efficiently at lower Mach numbers
  - can also produce static (takeoff thrust)
- Max. (main) combustion $T$ (T4) lower than ramjets
  - limited by turbine materials (stresses)
  - 1939:
    - 1300F (1000K) von Ohain/Whittle
  - current:
    - 3200-3500F (2000-2200K)

"Real" Turbojet Cycle Analysis

- As with ramjet analysis
  - components are NOT assumed to be reversible, will experience $p_o$ losses
    - for expansion/compression components, use adiabatic efficiency approach
    - for burners, use stagnation pressure ratio factors
  - combustors (burner, afterburner) do not achieve ideal heat release
    - include burner efficiencies
  - still assume no heat losses
- But for this analysis, will NOT assume $c_p = \text{constant}$ throughout engine
  - use appropriately “averaged” $c_p$ for each component
“Real” Turbojet Cycle Analysis

• **Step 1:**
  – draw cycle on $T$-$s$ diagram

• **Step 2:**
  – component by component analysis to find $u_e$

• **Step 3:**
  – calculate engine performance parameters

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**Diffuser** (subsonic)

– same as ramjet

$m_2 = m_a$

$T_{o2} = T_e \left(1 + \frac{\gamma_d - 1}{2} M^2\right)$

$p_{o2} = p_d \left(1 + \eta_d \frac{\gamma_d - 1}{2} M^2\right)^{\gamma_d / \gamma_d - 1}$

**Compressor**

– from class example

\[
\frac{p_{o3}}{p_{o2}} = \text{given, design choice} = P_{rc}
\]

$m_3 = m_2$

$T_{o3} = T_{o2} \left(1 + \frac{1}{\eta_c} \left[\left(\frac{p_{o3}}{p_{o2}}\right)^{\gamma_c - 1} \right]^{\gamma_c / \gamma_c - 1} \right)$

$W_c = m_c c_p \left(T_{o3} - T_{o2}\right)$

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Example 6

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“Real” Turbojet Cycle Analysis

• **Burner** (main combustor)
  - similar to ramjet
  \[ \dot{m}_t = \dot{m}_a (1 + f) \]
  \[ f = \frac{T_{o3} - 1}{(\eta_b \Delta h_R/c_p T_{o3}) - T_{o4}/T_{o3}} \]
  \[ P_{o4} = P_{o3} \]

• **Turbine**

\[ 4 \dot{m}_5 \quad P_{o4}, T_{o4} \quad T \quad 5 \dot{m}_5 \quad P_{o5}, T_{o5} \quad W_T \]

• **Afterburner**

\[ 5 \dot{m}_5 \quad P_{o5}, T_{o5} \quad AB \quad 6 \dot{m}_6 \quad P_{o6}, T_{o6} \]

• **Nozzle**
  - similar to ramjet
  \[ \dot{m}_e = \dot{m}_6 \]
  \[ T_e = T_{o6} \left( 1 - \eta_a \left[ 1 - \left( \frac{P_e}{P_{o6}} \right)^{\gamma_a - 1} \right] \right) \]
  \[ u_e = \sqrt{2 c_{p_n} (T_{o6} - T_e)} \]
Turbojet Performance

• Performance parameters
  – similar to ramjet, just need to add ab fuel

\[
ST = \frac{\tau}{m_a} = \left[ (1 + f + f_{ab})u_e - u \right] + \frac{(p_e - p_a)A_e}{m_a}
\]

\[
TSFC = \frac{m_f + m_{f_{ab}}}{\tau} = \frac{f + f_{ab}}{ST}
\]

\[
\eta_o = \frac{1}{\eta_{TSFC} \Delta h_R}
\]

\[
\eta_{th} = \frac{\Delta KE}{(m_f + m_{f_{ab}}) \Delta h_R} = \frac{(1 + f + f_{ab})u_e^2 - u^2}{(f + f_{ab}) \Delta h_R}
\]

\[
\eta_p = \frac{\eta_o}{\eta_{th}}
\]