AAE 538: Air-Breathing Propulsion

Lecture 12: Analysis of Real Engine Cycles

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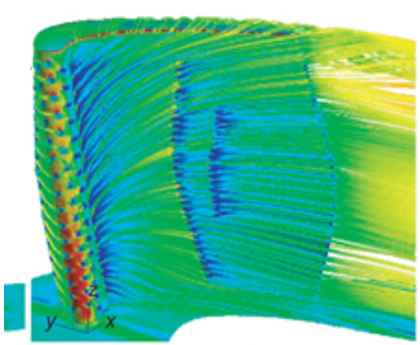
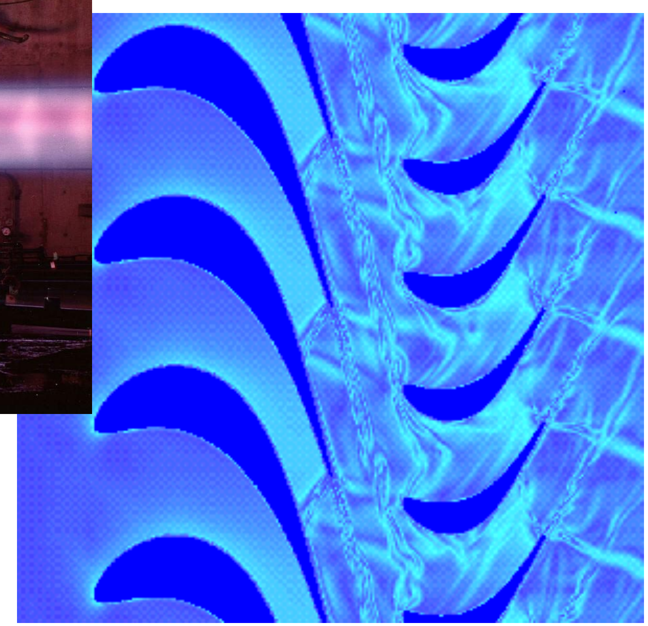
The Real Turbojet Cycle

- Now that we have a basic understanding of ideal turbojet engines, we can relax some of the assumptions associated with the ideal cycle to gain a better perspective on actual turbojet engine performance.
    - Unfortunately, this analysis is not nearly as elegant and the results now become more difficult to interpret.
    - However, a systematic application of the results will permit more accurate thrust and specific fuel consumption characteristics for actual jet engines.





The Real Turbojet Cycle

- In real turbojet engines, real processes are ________________________ using the concept of the process efficiency.
  - Consider the h-s diagram for a compression process
    - In an isentropic process, the full stagnation enthalpy and stagnation pressure are recovered: $h_{0,S}$ and $p_{0,S}$.
    - Considering irreversibility (friction and shocks) and heat transfer, the actual recovered enthalpy and pressure are h_0 and p_0.
  - We can define an efficiency, η, which characterizes the extent to which this process is isentropic.
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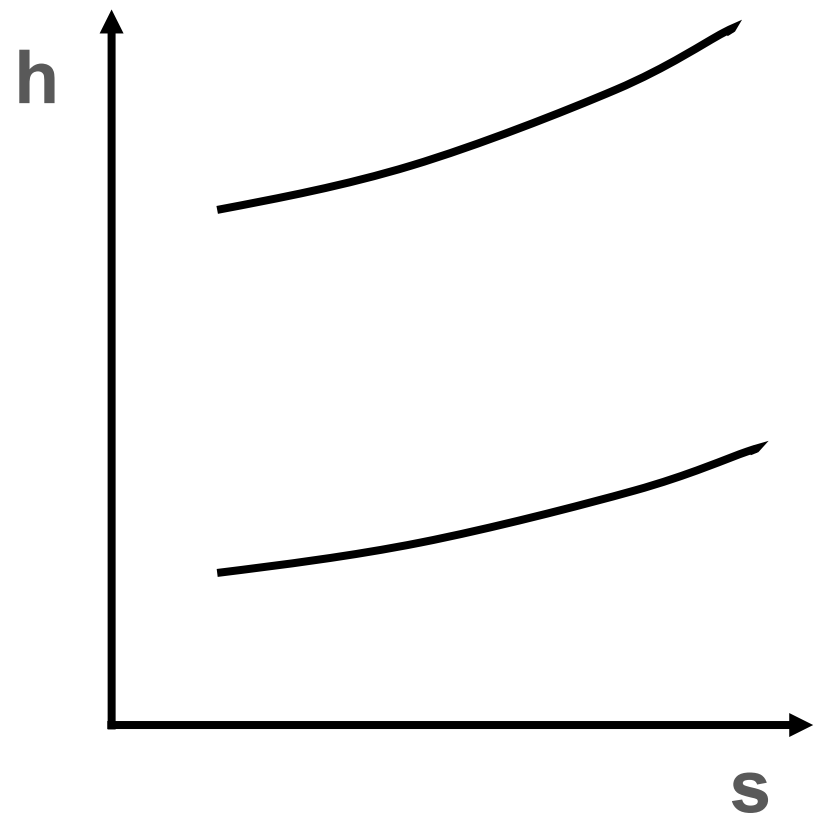

The Real Turbojet Cycle

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- This expression implies that, for a given enthalpy change, η measures the ____.
  - In many cases, it remains a valid assumption to treat the real flow as adiabatic so that the efficiency only needs to account for friction losses, flow separation, shocks, etc.
  - For calorically-perfect gases,

Therefore, the actual stagnation pressure obtained in the non-isentropic process can be written:

The Real Turbojet Cycle

- Using these notions, the overall h-s diagram for a real turbojet can be generated
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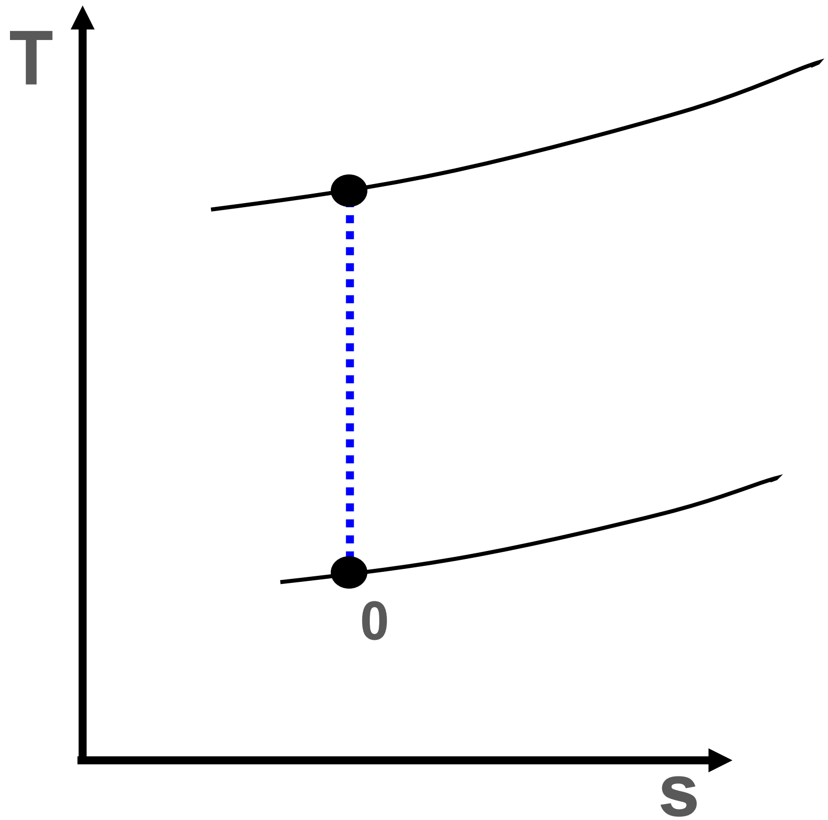
Real Diffusers

- The diffuser acts as a compression device, therefore our previous analysis of the anisentropic compression process can be directly applied.



Real Diffusers

- Defining the diffuser efficiency in terms of energy recovery

$$\eta_d =$$

  - But, through the definition of the stagnation temperature and stagnation pressure

$$\frac{T_{o,2'}}{T_0} = \left(\frac{p_{o,2}}{p_0}\right)^{\frac{\gamma-1}{\gamma}}$$

  - And, since we are assuming the deceleration process in the diffuser is adiabatic (not too bad for a turbojet), the stagnation (or recovery) temperature can be calculated in the same manner as in an ideal turbojet.

$$\frac{T_{o,2s}}{T_0} =$$

Real Diffusers

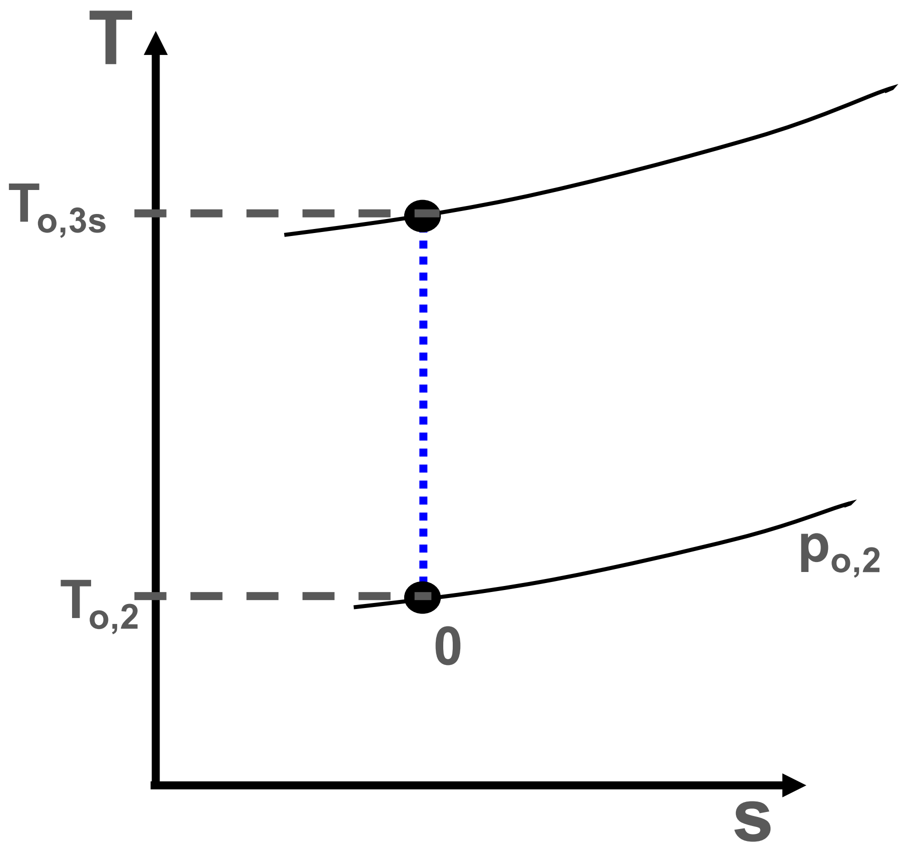
- For a given freestream static pressure (p_o), and freestream Mach number (M_o), we can determine the stagnation pressure entering the compressor at state 2

- The diffuser efficiency is a strong function of the free-stream Mach number
  - Shock losses can be very strong for supersonic configurations

- Typical values of η_d lie between 0.7 and 0.95 with ______________________ applications realizing ____________________efficiency values.

Real Compressors

- In the case of the compressor, we generally consider the compressor pressure ratio to be a given quantity. Therefore, we want to find the stagnation temperature ratio which corresponds to the desired pressure ratio for a given compressor efficiency, η_c.



Real Compressors

- Now the isentropic ΔT is less than the real ΔT

$$\eta_c = \frac{h_{o,3s} - h_{o,2}}{h_{o,3} - h_{o,2}} =$$

Such that the desired temperature ratio becomes:

$$\frac{T_{o,3}}{T_{o,2}} = 1 + \frac{1}{\eta_c}\left[\left(\frac{p_{o,3}}{p_{o,2}}\right)^{(\gamma-1)/\gamma} - 1\right]$$

- The compressor efficiency accounts for:
  -
  -
  -
- A major factor in the design of an efficient engine, typical values lie between 0.87 and 0.94 for well-designed compressors.

Real Combustors

- In the combustor there are really two efficiencies that come into play.
  - The first efficiency can be derived to account for the loss in stagnation pressure due to heat addition and friction within the burner.
    - By considering the combustor as a combination of Fanno and Rayleigh flows, we could estimate this quantity by knowing the ________________________ of the flow entering the burner and the details of the heat addition process.
    - Since the Mach number in the burner is _______________________ and the chamber characteristics are extremely difficult to quantify accurately, we will still neglect this effect, for the time being.
  - The second, additional efficiency, η_b, results from ____________________________.
    - From our analysis of thermochemistry, we know that this could have a very large impact.
    - For an incomplete combustion process, the energy added to the stream will be ________________ by the factor η_b so that the energy equation for the combustor becomes:

Real Combustors

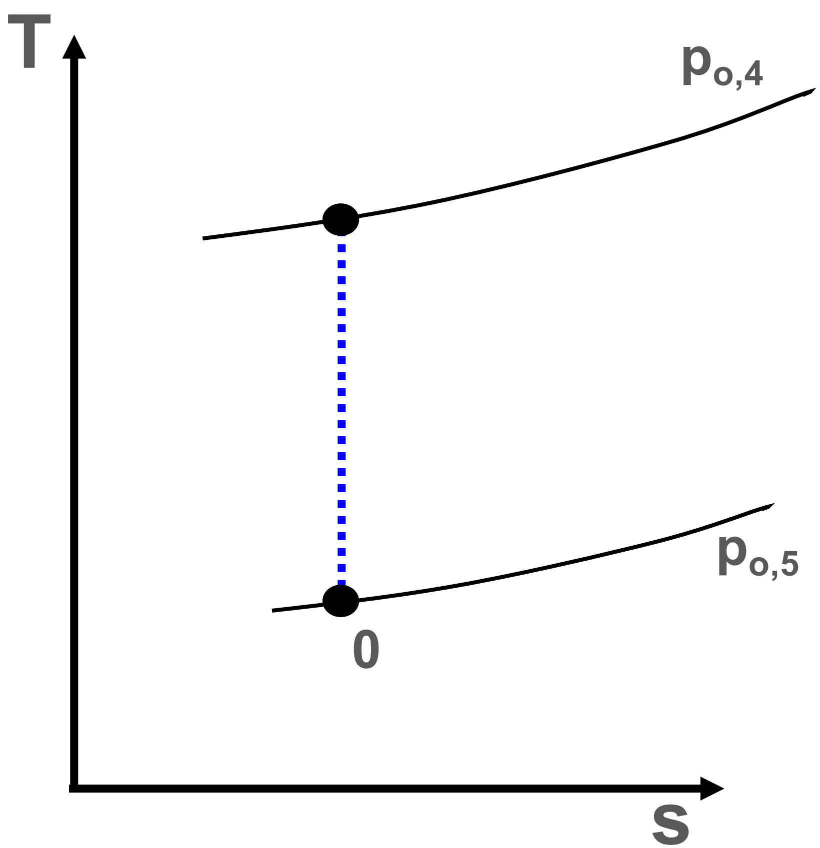
- Rearranging and introducing the fuel/air ratio gives

$$f =$$

- The ‘combustion efficiency’ is typically greater than 99% for well-designed burners.

Real Turbines

- For a given turbine work requirement,
  - Irreversible processes cause the actual turbine pressure ratio to be ____________________ the isentropic result calculated for the ideal turbojet.
  - Additionally, the compressor requires more work than in the isentropic condition.



Real Turbines

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- These two factors cause the turbine work requirement (and actual associated pressure ratio) to be much larger for an actual engine.
    - Since the flow through the turbine is an expansion process, the turbine efficiency is expressed in an inverse sense, relative to our derivation for the compression process.

$$\eta_t =$$

Where this relation essentially states that the actual temperature drop is less than the isentropic temperature drop through the turbine. (reduced work extraction)

Real Turbines

- Proceeding as before, we substitute and rearrange to show

$$\frac{T_{o,5}}{T_{o,4}} =$$

- As in the case of the ideal turbojet, a power balance between the turbine and the compressor allows us to compute the pressure ratio (and temperature ratio) across the turbine.
  - Equating the work out of the turbine to the work into the compressor gives
  - If we assumed that $f \ll 1$, and $c_{p,c} = c_{p,t} = c_p$ (which isn't a great assumption), we can factor out $T_{0,4}$ and $T_{0,5}$ from this relation.

Real Turbines

- Substituting the equations for $T_{o,3}/T_{o,2}$ and $T_{o,5}/T_{o,4}$ gives

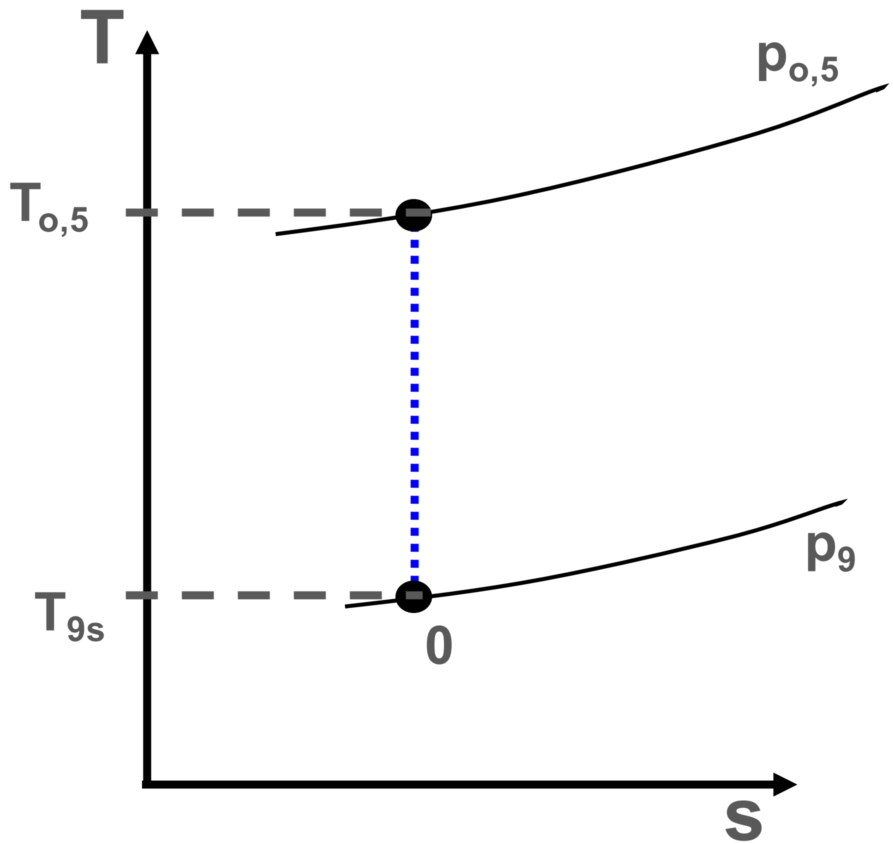
  Which tells us that

- The above relation allows one to calculate the required turbine pressure ratio to drive the compressor.
  - In practice, the turbine must also provide a small amount of additional work to drive electric generators and hydraulic systems for use as aircraft power.

- Turbine efficiencies account for friction and leakage losses across the device
  - Typical values are between 0.92 and 0.98 for well-designed turbines
  - Note that the turbine efficiencies are higher than compressor efficiencies.

Real Nozzles

- Assuming no afterburner is present, our conditions at state '5' are equal to those at state '7'
- As in our expanding flow through the turbine, the actual enthalpy drop across the nozzle will be less than the isentropic change (same as turbine)



Real Nozzles

- Proceeding, as above, we may write:

$$\eta_n = \frac{h_{o,7} - h_9}{h_{o,7} - h_{9s}} =$$

- Rearranging this result permits us to solve for the static temperature at the end of the nozzle:

$$\frac{T_9}{T_{o,5}} =$$

Real Nozzles

- If the velocity at station '7' is negligible compared to the enthalpy at that location, then we can write:

$$u_9 =$$

Which illustrates our rationale for defining the nozzle efficiency in terms of a difference between a stagnation and a static enthalpy

- Substituting for $T_9/T_{o,5}$ gives us a relation for the nozzle exit velocity in terms of known parameters, as long as we can calculate the stagnation state of the gases exiting the turbine. Assuming that the nozzle is perfectly expanded ($p_9 = p_0$) to maximize thrust, we find

Real Engines

Summary and Results

- Now that we've introduced component efficiencies, we cannot write a simple equation for the engine thrust as we did in the previous discussion of ideal engine.
- Instead, we must continue this procedure of 'stepping through' the engine, eventually calculating the specific thrust and specific fuel consumption of the real turbojet.
  - As before, assuming that $\mathrm{p}_9 = p_0$ we can write the specific thrust as
  - To calculate the actual thrust, one needs to know the state '0' as well as the capture area of the inlet in order that the mass flow rate $\dot{m}_0$, can be calculated.

Real Turbojet Example

Compute the Specific Thrust and the Specific Fuel Consumption of an ideal turbojet engine operating with the following parameters:

Given:

$\pi_c = 20$

$T_{o,4} = 1800\ F$

$\Delta H_B = 16000\ BTU/lbm$

$M_0 = 0.6$

$\gamma = 1.4$

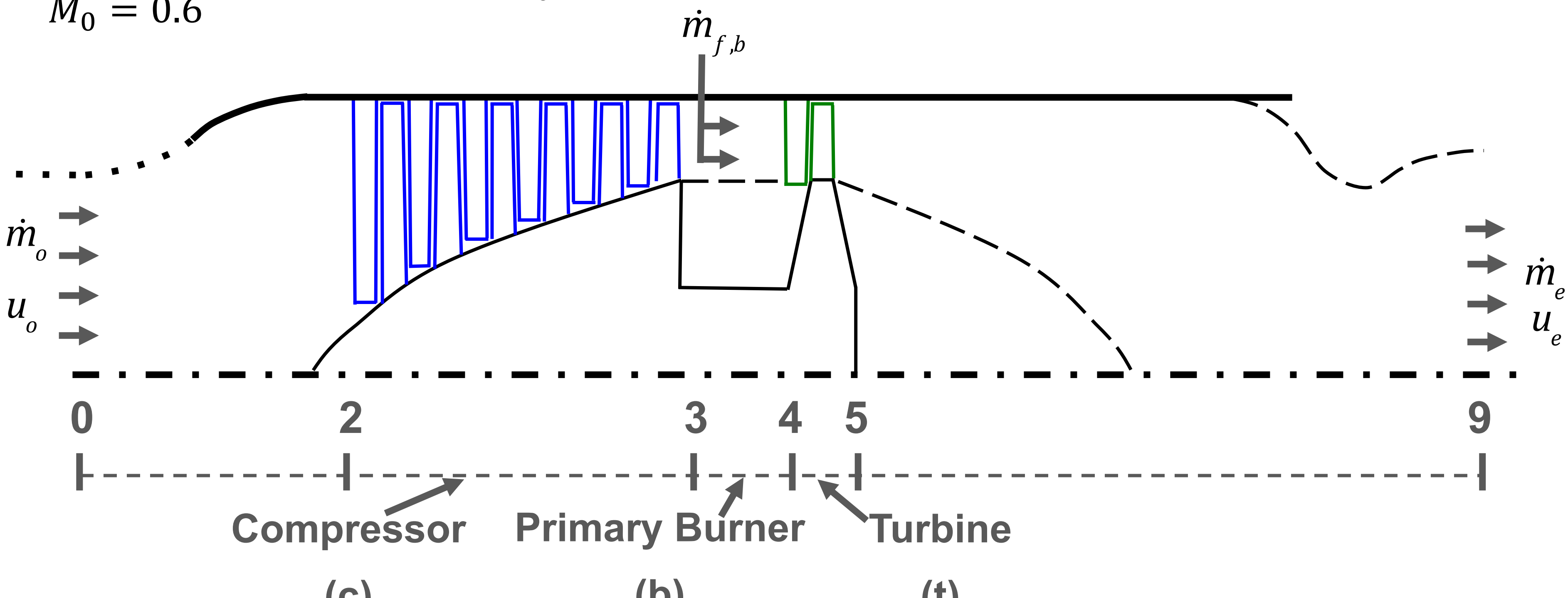
$c_p = 0.24 \dfrac{BTU}{lbm\ R} = \text{constant}$

$p_0 = 6\ psi$

$T_0 = 460\ R$

Assume:

(Measured) component efficiencies:



Real Turbojet Example

Find: $T/\dot{m}\ ,\ S$

Starting at state 2:

Moving through the compressor to state 3:

Real Turbojet Example

Now in the combustor, we still assume negligible total pressure loss, but we are now accounting for thermal energy impact of incomplete combustion.

Real Turbojet Example

We use our power balance to get to state 5:

Solving for state 9 to compute engine performance:

Real Turbojet Example