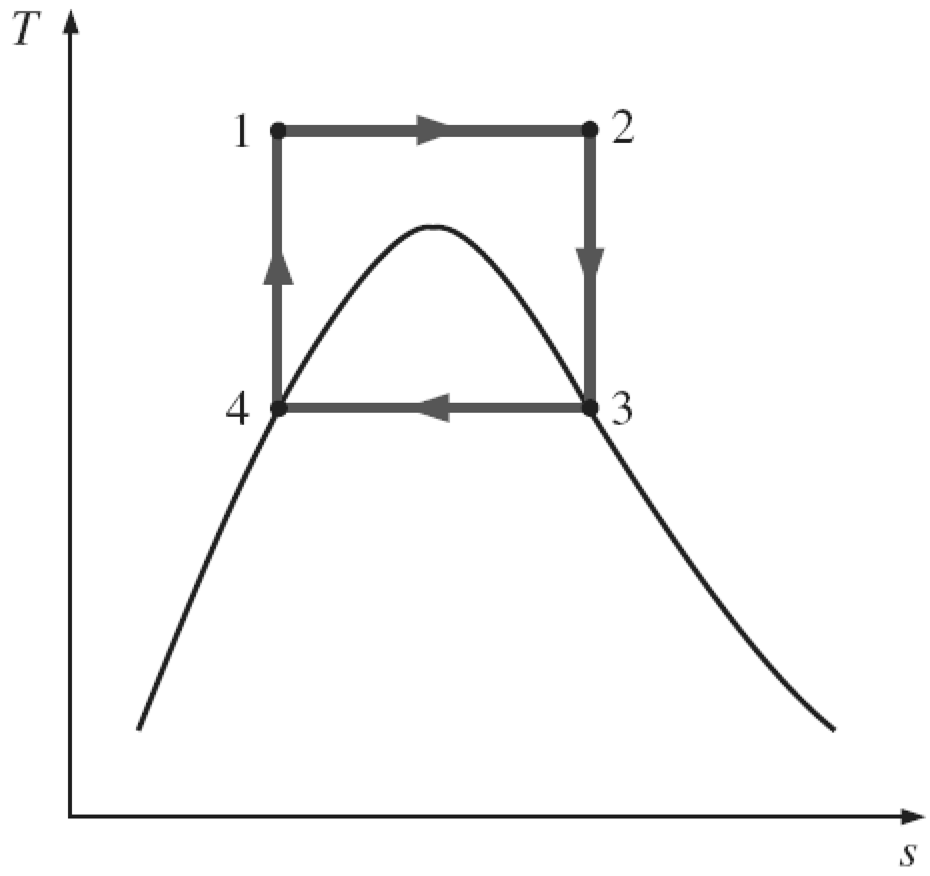
- Recap: Lecture 30, 27th March 2014, 0930-1030 hrs.
  - Carnot vapour cycle
  - Rankine cycle
  - Simple Rankine cycle
  - Processes in the cycle
  - Improving cycle performance



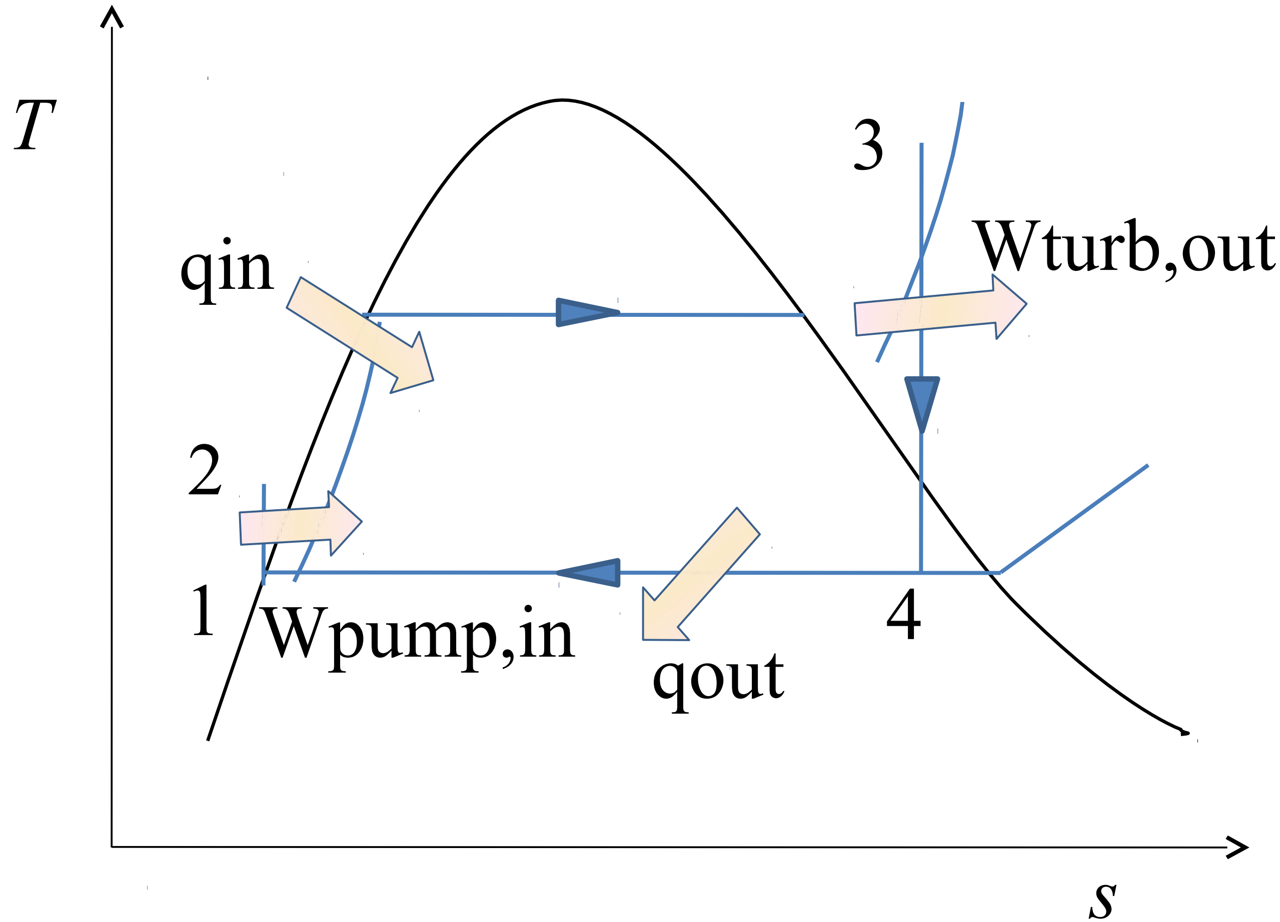
Case 2: Carnot cycle partially outside the saturation dome

- Isentropic compression to extremely high pressures □ difficult to achieve
- Not possible to have isothermal heat transfer at variable pressures.
- Therefore Carnot cycle cannot form a realistic model for vapour power cycles.
- The ideal cycle for vapour is the Rankine cycle.

Rankine cycle

- Rankine cycle is the ideal cycle for vapour power cycles.
- The ideal Rankine cycle does not involve any internal irreversibilities.
- The ideal cycle consists of the following:
  - 1-2 Isentropic compression in a pump
  - 2-3 Constant pressure heat addition in a boiler
  - 3-4 Isentropic expansion in a turbine
  - 4-1 Constant pressure heat rejection in a condenser

Rankine cycle



The ideal Rankine cycle

Rankine cycle

- All the components are steady flow systems.
- The energy balance for each sub-system can be expressed as:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta h$$

$$\text{Pump}: w_{pump,in} = h_2 - h_1 = v(P_2 - P_1)$$

$$\text{Boiler}: q_{in} = h_3 - h_2$$

$$\text{Condensor}: q_{out} = h_4 - h_1$$

$$\text{Turbine}: w_{out} = h_3 - h_4$$

Rankine cycle

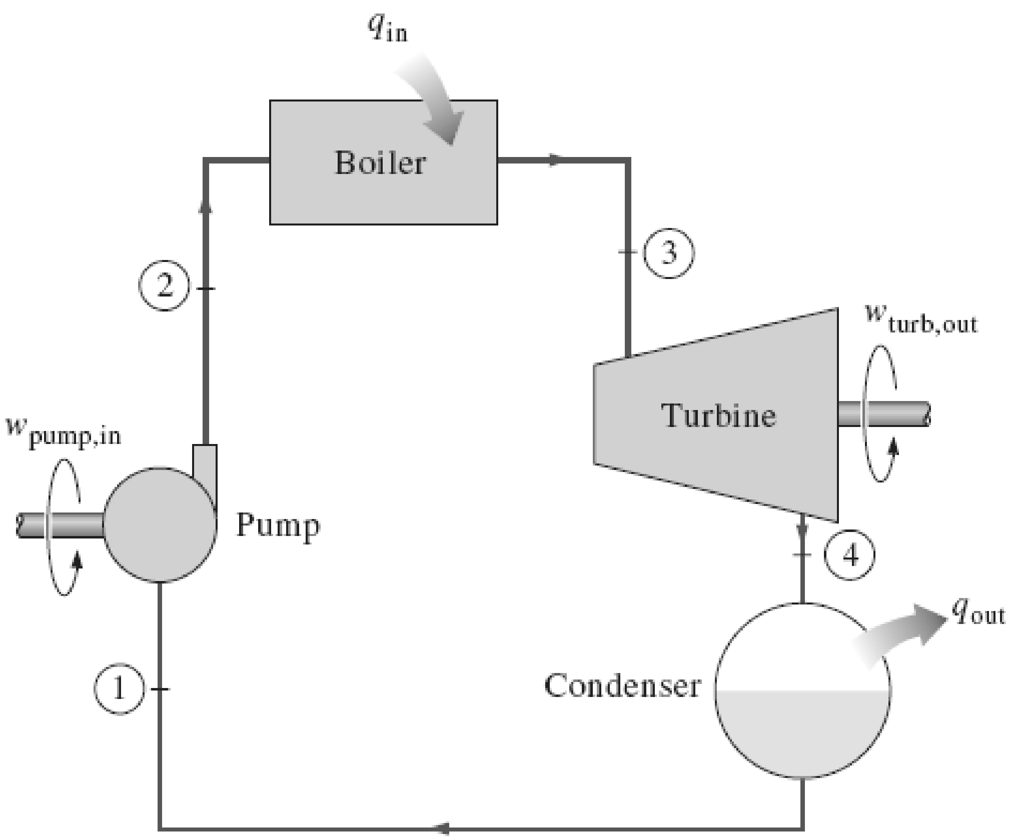
- The thermal efficiency of the ideal Rankine cycle under the cold air standard assumptions becomes:

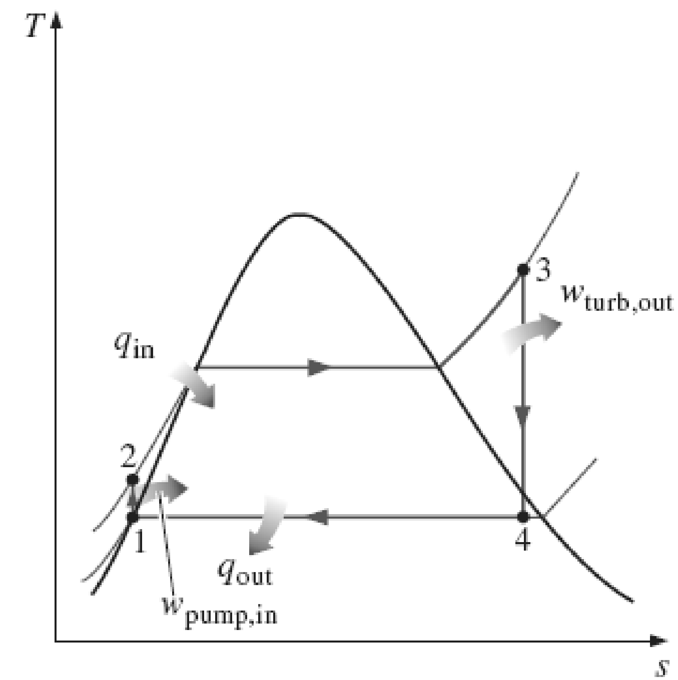
$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

where, $w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$

Rankine cycle

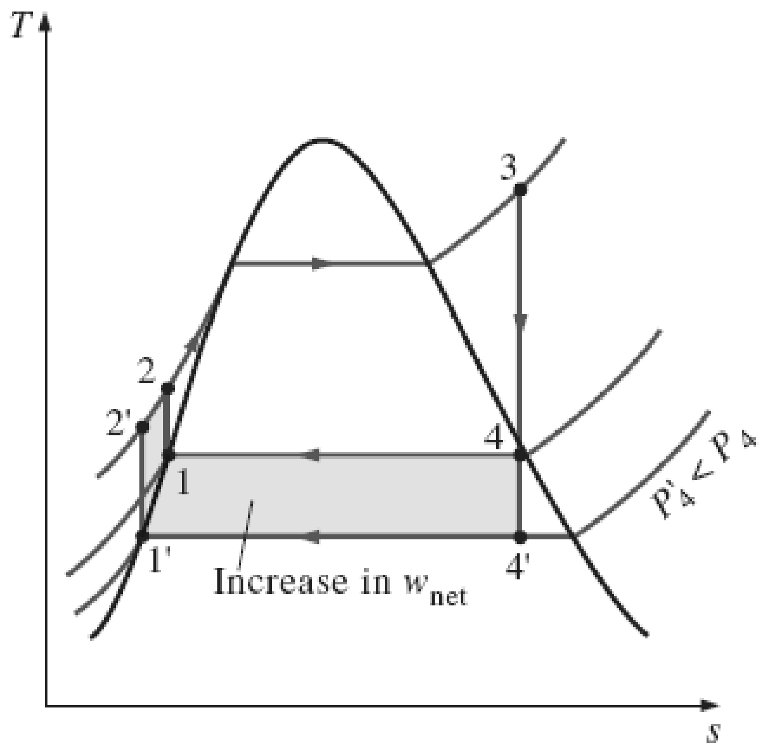
- Rankine cycles can also be operated with reheat and regeneration.
- The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages.
- A Rankine cycle with reheat and regeneration offer substantially higher efficiencies as compared to a simple Rankine cycle.



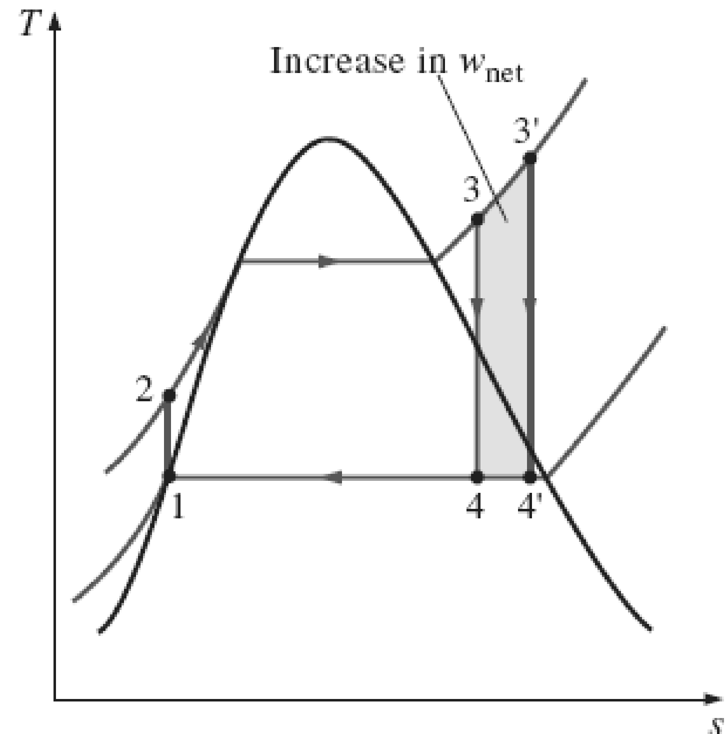


Simple Rankine cycle

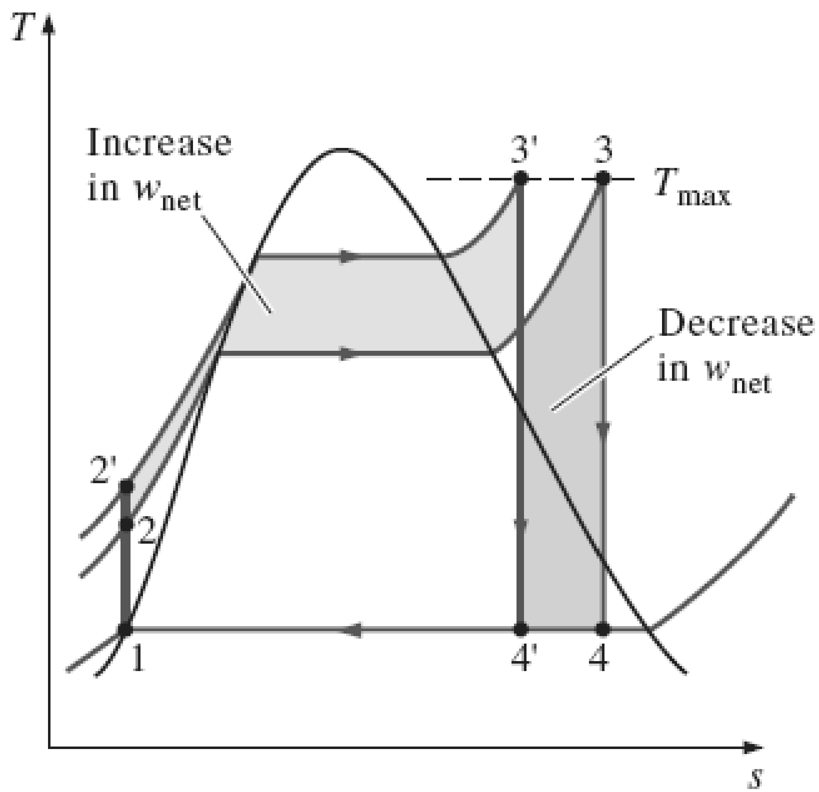
- Improving efficiency of Rankine cycle
  - Lowering the condenser pressure
  - Superheating the steam to high temperatures
  - Increasing the boiler pressure
  - Reheating, intercooling and regeneration



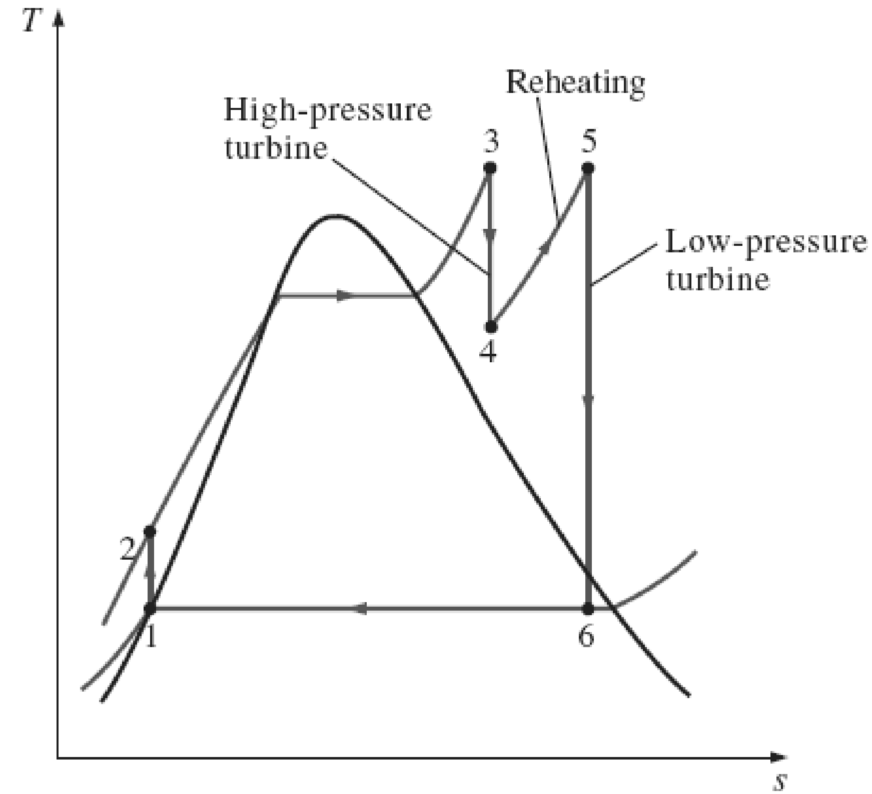
The effect of lowering the condenser pressure on the ideal Rankine cycle.



The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.



The effect of increasing the boiler pressure on the ideal Rankine cycle.

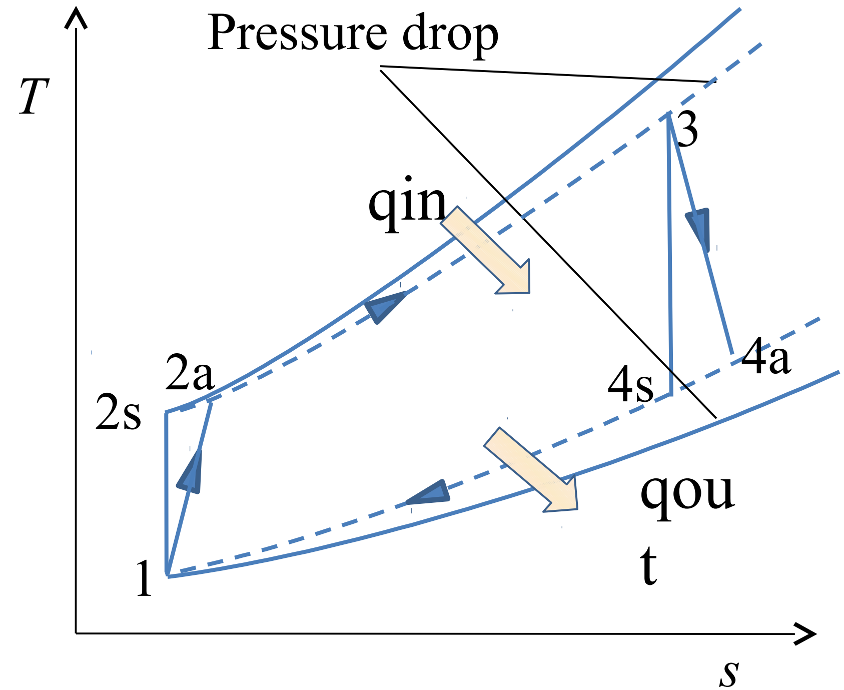


The ideal reheat Rankine cycle.

Actual/Real Brayton cycle

- Actual Brayton cycles differ from the ideal cycles in all the four processes.
- The compression process and expansion processes are non-isentropic.
- Pressure drop during heat addition and heat rejection.
- The presence of irreversibilities causes the above deviations.

Actual/Real Brayton cycle



Actual Brayton cycle *T-s* diagram

Actual/Real Brayton cycle

- The deviation of actual compressors and turbines from the isentropic versions can be accounted for by using the isentropic efficiencies.

$$\eta_C = \frac{\text{Isentropic work}}{\text{Actual work}} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{\text{Actual work}}{\text{Isentropic work}} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

- Where, *2a* and *4a* are the actual states at the compressor and turbine exit and *2s* and *4s* are the corresponding isentropic states.

Actual/Real Brayton cycle

- As a result of non-isentropic compression and expansion, the compressor needs more work than the ideal cycle and turbine generates less work.
- Isentropic efficiencies reflect the amount of deviation of the actual compression/expansion processes from the ideal.
- Total pressure losses in the heat addition/rejection processes also need to be considered.

Actual/Real Brayton cycle

- Other differences between ideal and actual Brayton cycles
  - Change of specific heats with temperature
  - Heat exchanger effectiveness (in case of regenerative cycles)
  - Mass flow rate of fuel
  - Combustion efficiency
- These parameters are often used in actual cycle analysis.

Actual/Real Brayton cycle

- Variants of the simple Brayton cycle
  - Reheating
  - Intercooling
  - Regeneration
- Actual cycles with the above will be different from the ideal cycles in terms of the irreversibilities present.
- Isentropic efficiencies, total pressure losses, heat exchanger effectiveness for each additional components of the cycle.

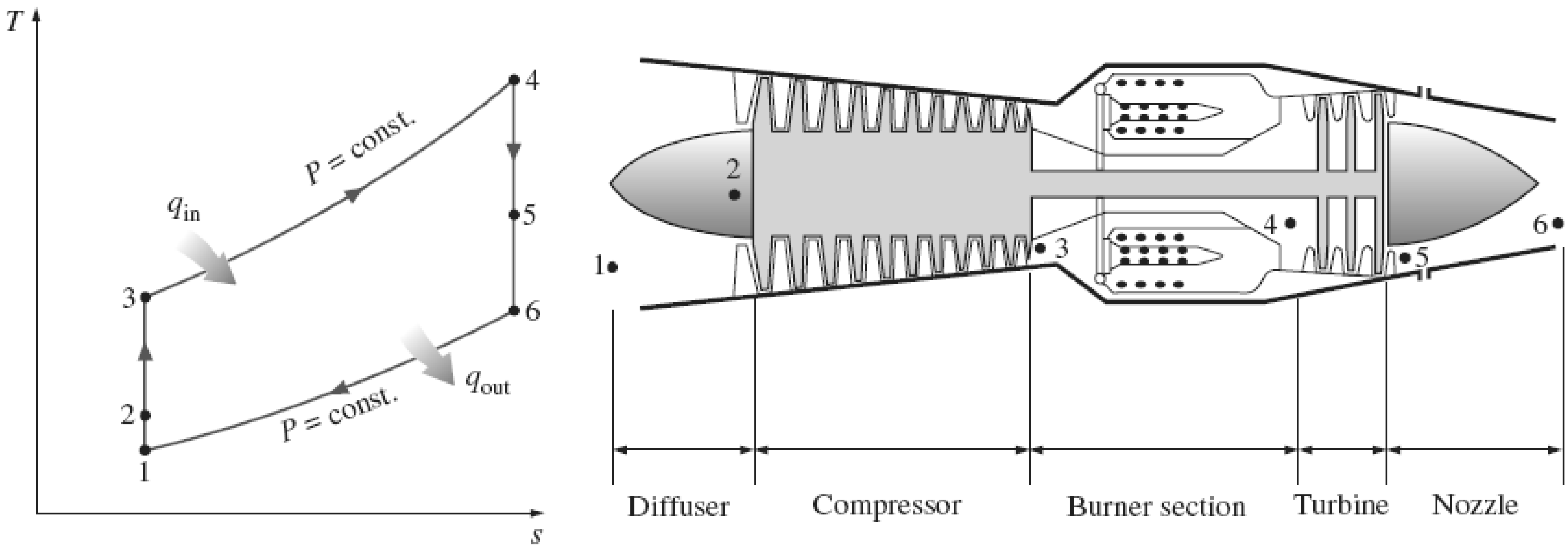
Actual/Real Brayton cycle

- Actual Brayton cycle with intercooling
  - Isentropic efficiencies of each stage of intercooling
  - Heat exchanger effectiveness of the intercooling duct
- Actual Brayton cycle with reheating
  - Isentropic efficiencies of each stage of reheating
  - Total pressure loss and combustion efficiency during reheating

Actual/Real Brayton cycle

- Actual Brayton cycle with regeneration
  - Heat exchanger effectiveness
- Actual Brayton cycle with all three of these modifications need to be analysed considering the above discussed irreversibilities.

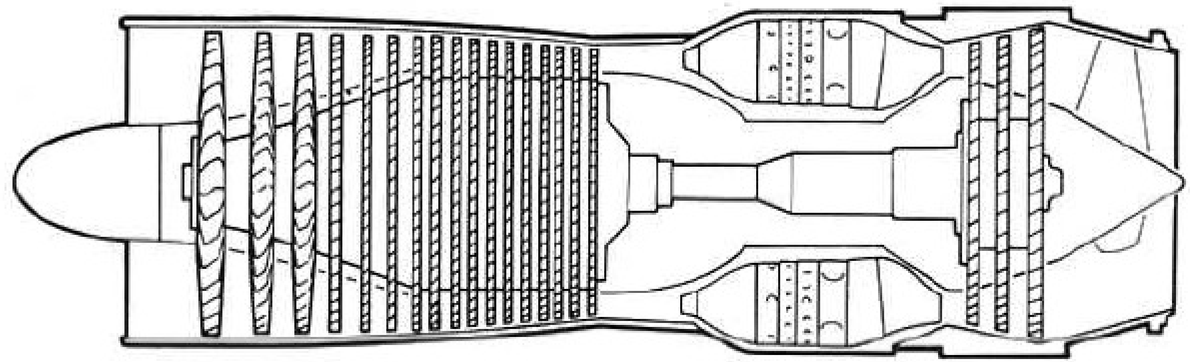
- Ideal Jet Propulsion cycles
  - Slightly different from the ideal Brayton cycle
  - Gases are not completely expanded in a turbine
  - Partly in turbine and remainder in nozzle
  - Net work output of the jet propulsion cycle is zero
  - thrust developed in a turbojet engine is the unbalanced force that is caused by the difference in the momentum of the low-velocity air entering the engine and the high-velocity exhaust gases leaving the engine



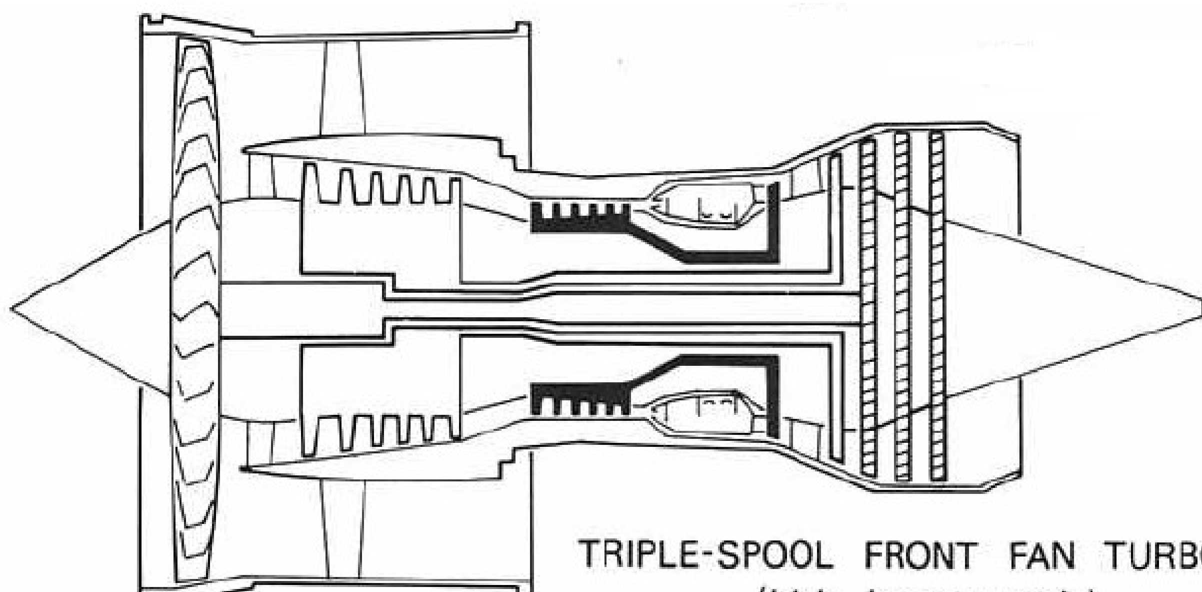
Basic components of a turbojet engine and the *T-s* diagram for the ideal turbojet cycle.

Types of jet engines

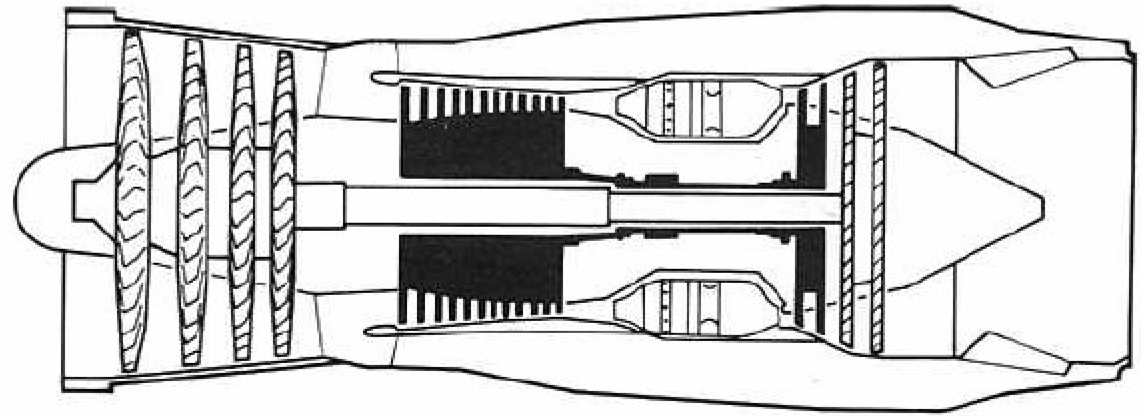
- Ramjet:
  - Mach number range 1.5-3.0,
  - Application: Military
- Scramjet:
  - Mach 3.0-10.0
  - Application: Military, civil
- Turbojet:
  - Mach 0-2.5
  - Application: Military, civil?
- Turbofan:
  - Mach 0-0.85
  - Application: Civil, military?
- Turboprop:
  - Mach 0-0.75
  - Application Civil, military
- Turboshaft:
  - Mach 0-0.55
  - Application: Civil, military



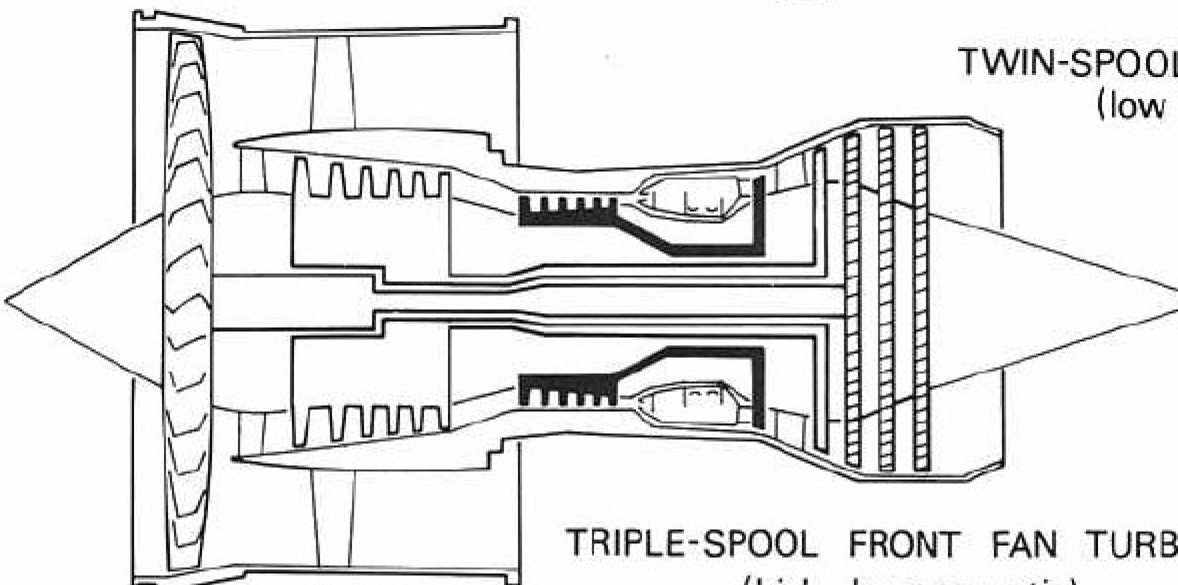
SINGLE-SPOOL AXIAL FLOW TURBO-JET



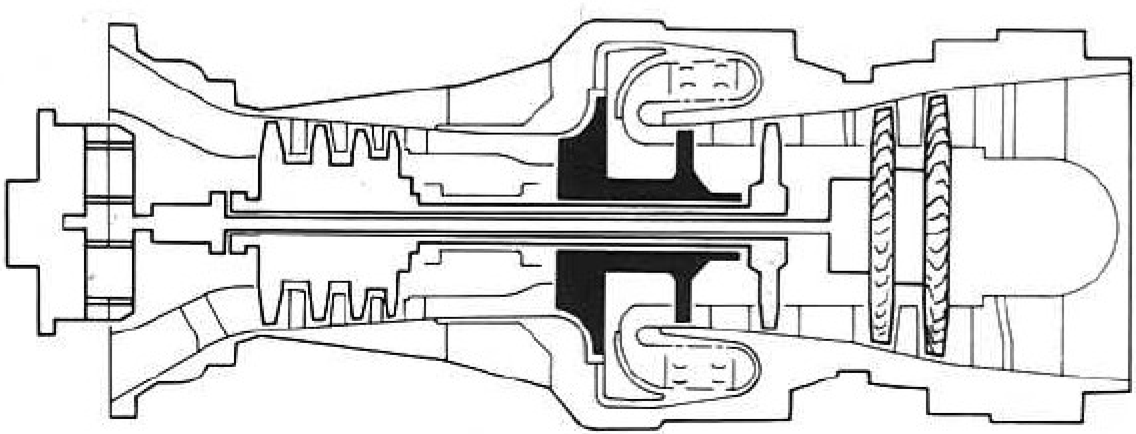
TRIPLE-SPOOL FRONT FAN TURBO-JET
(high by-pass ratio)



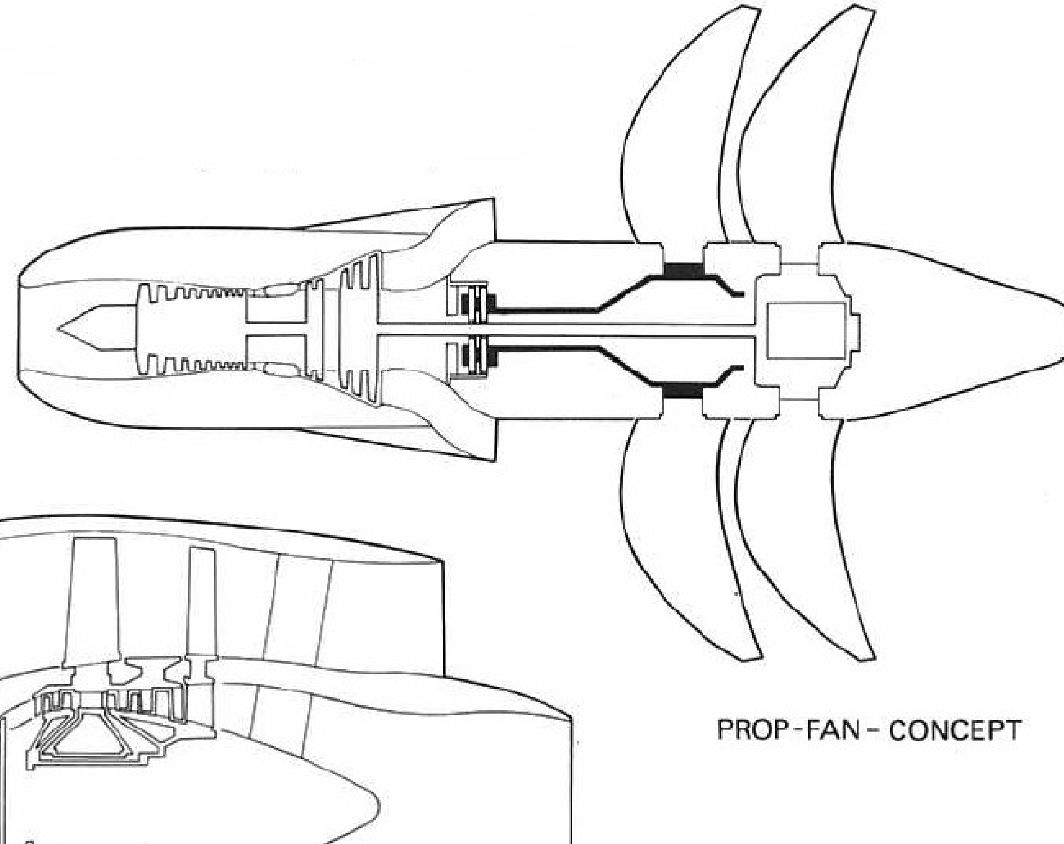
TWIN-SPOOL BY-PASS TURBO-JET
(low by-pass ratio)



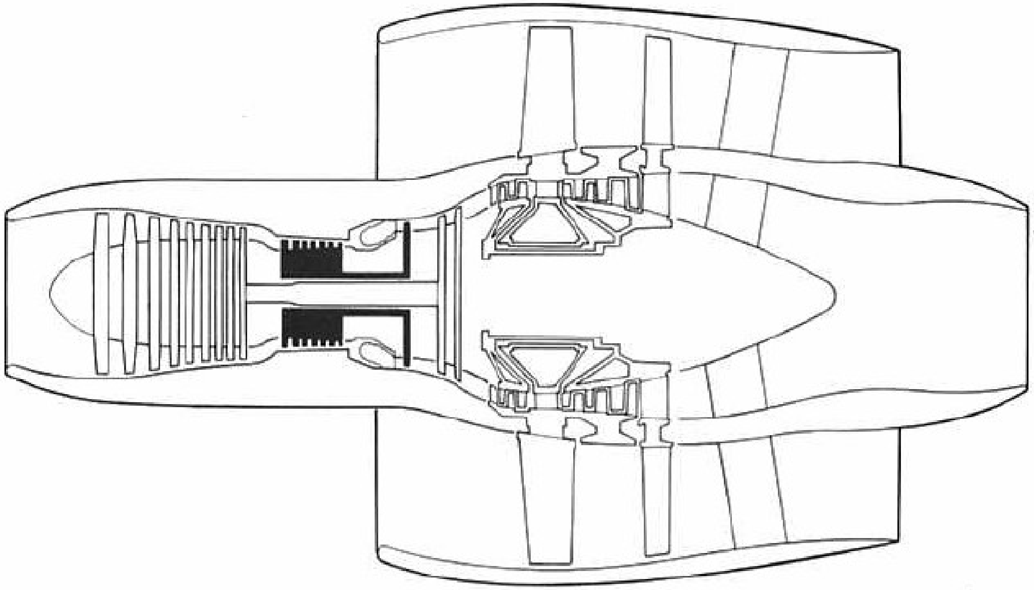
TRIPLE-SPOOL FRONT FAN TURBO-JET
(high by-pass ratio)



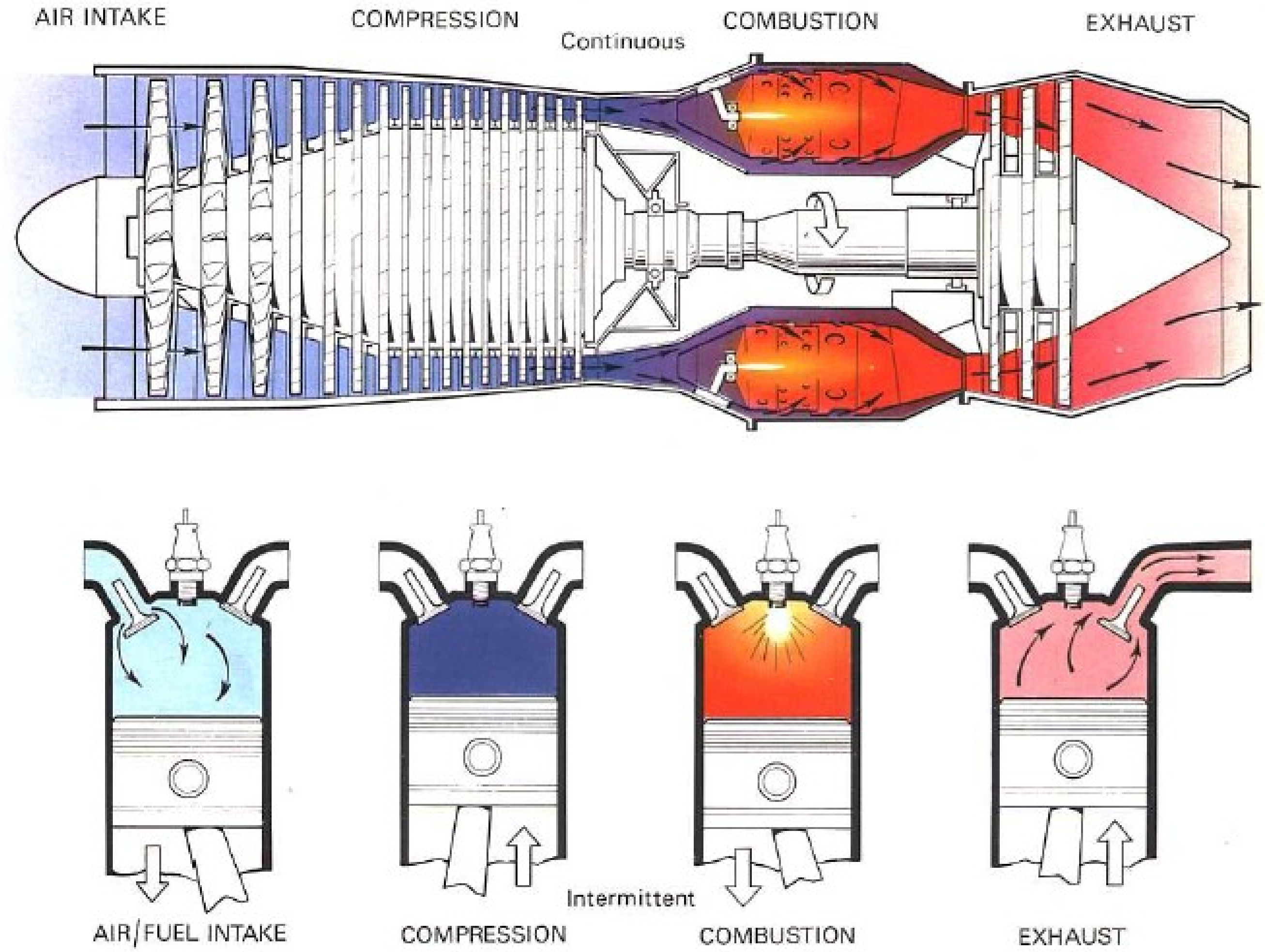
TWIN-SPOOL TURBO-SHAFT (with free-power turbine)



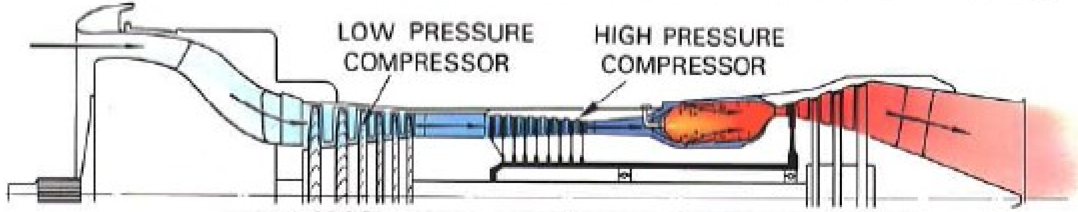
PROP-FAN - CONCEPT



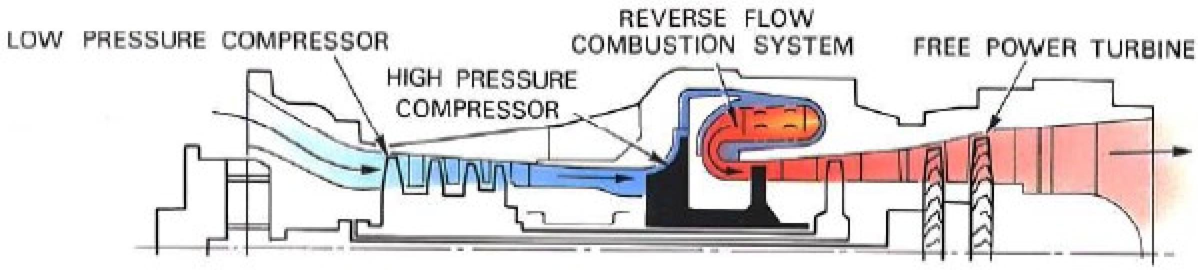
CONTRA-ROTATING FAN - CONCEPT (high by-pass ratio)



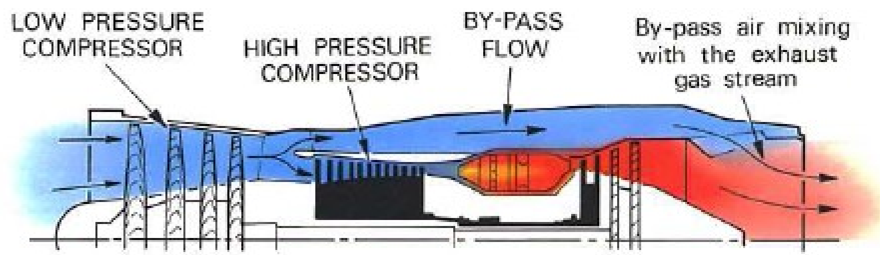
A Comparison between gas turbine engine and a piston engine



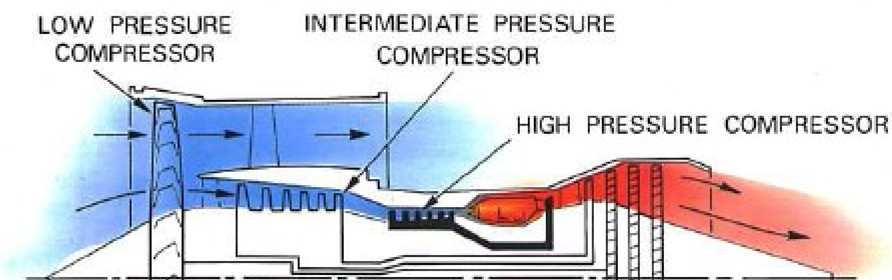
TWIN-SPOOL AXIAL FLOW TURBO-PROPELLER ENGINE



TWIN-SPOOL TURBO-SHAFT ENGINE (with free power turbine)



TWIN-SPOOL AXIAL FLOW BY-PASS TURBO JET ENGINE (low by-pass ratio)



TRIPLE-SPOOL AXIAL FLOW FRONT FAN TURBO JET ENGINE (high by-pass ratio)

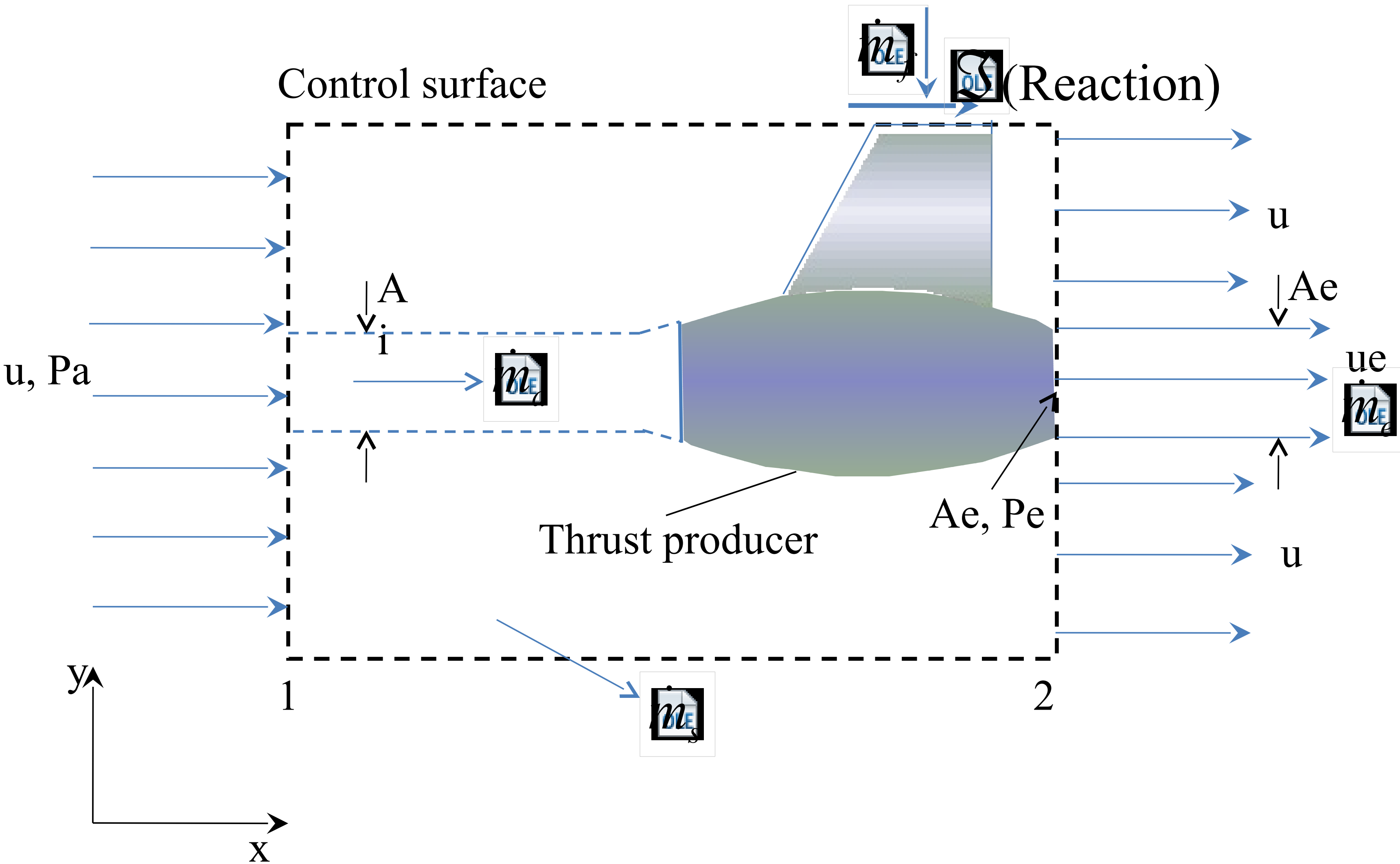
Gas turbine cycles

- Gas turbine engines operate on Brayton cycles.
- Ideal Brayton cycle is a closed cycle, whereas gas turbines operate in the open cycle mode.
- Ideal cycle assumes that there are no irreversibilities in the processes, air behaves like an ideal gas with constant specific heats, and that there are no frictional losses.

Thrust and efficiency

- We will now derive expressions for thrust and efficiency of air-breathing engines from the momentum and energy equations.
- We shall consider a generalized thrust producing device with a single inlet and single exhaust.
- We assume that the thrust and conditions at all points within the control volume do not change with time.

The thrust equation



The thrust equation

- The reaction to the thrust, , is transmitted to the support. The engine thrust is thus the vector summation of all forces on the internal and external surfaces of the engine.
- Therefore,

$$\sum \vec{F} = \int_{CS} \vec{u}\,\rho(\vec{u}.\vec{n})dA$$

- Considering the components of force and the momentum flux in the x-direction only,

$$\sum F_x = \int_{CS} u_x\,\rho(\vec{u}.\vec{n})dA$$

The thrust equation

- The pressure and velocity can be assumed to be constant over the entire control surface, except over the exhaust area, Ae.
- The net pressure force acting on this control volume is *(Pa–Pe)Ae*.
- The only other force acting on the control volume is the reaction to the thrust, .
- Adding up the forces in the x-direction,

$$\sum F_x = (P_a - P_e)A_e + \Im$$

The thrust equation

- The mass flow that enters the capture area, *Ai*, is $\dot{m}_a = \rho u A_i$
- Similarly, the mass flow crossing the exhaust area *Ae*, is,
- Also, $\dot{m}_e = \rho_e u_e A_e$

  Or, $\dot{m}_e = \dot{m}_a + \dot{m}_f$
- Continuity equation for the CV gives,

$$\dot{m}_f = \rho_e u_e A_e - \rho u A_i$$

$$\rho_e u_e A_e + \rho u (A - A_e) + \dot{m}_s - \dot{m}_f - \rho u A = 0$$

$$\text{Rearranging, } \dot{m}_s = \dot{m}_f + \rho u A_e - \rho_e u_e A_e$$

$$\text{Which is, } \dot{m}_s = \rho u (A_e - A_i)$$

The thrust equation

- From the momentum balance across the CV,

$$\int_{CS} u_x \rho(\vec{u}.\vec{n})dA = \dot{m}_e u_e + \dot{m}_s u + \rho u(A - A_e)u - \dot{m}_a u - \rho u(A - A_i)u$$

- This is the net outward flux of x-momentum.
- This equation reduces to

$$\int_{CS} u_x \rho(\vec{u}.\vec{n})dA = \dot{m}_e u_e - \dot{m}_a u$$

- From the force balance equation, we have,

$$\Im = \dot{m}_e u_e - \dot{m}_a u + (P_e - P_a)A_e$$

The thrust equation

- If we define fuel-air ratio,

$$\Im = \dot{m}_a\left[(1+f)u_e - u\right] + (P_e - P_a)A_e$$

- This is the generalised thrust equation for air-breathing engines.
- The term *(Pe–Pa)Ae* is not zero only if the exhaust jet is supersonic and the nozzle does not expand the exhaust jet to ambient pressure.
- However if *Pa* « *Pe*, it can be substantial contribution.