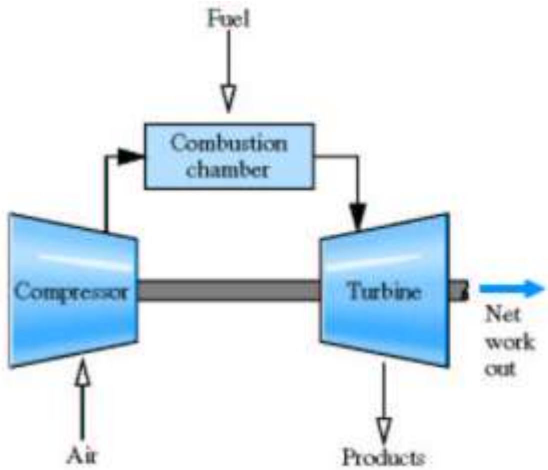
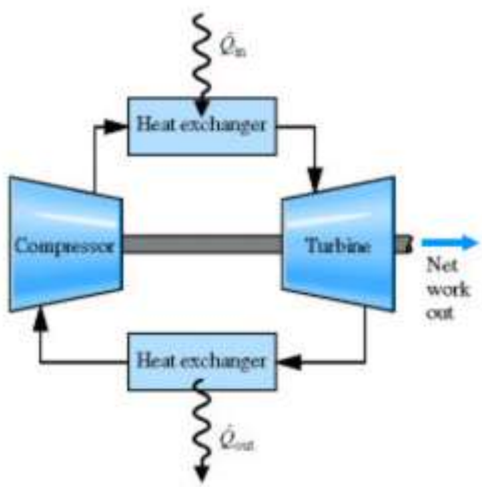
Gas Turbine Power Plants

Gas Turbine Power Plants are lighter and more compact than vapor power plants. The favorable power-output-to-weight ratio for gas turbines make them suitable for transportation.



Air-standard Brayton Cycle



For steady-state: $0 = \frac{\dot{Q}_{CV}}{\dot{m}} - \frac{\dot{W}_{CV}}{\dot{m}} + (h_{in} - h_{out})$

1 → 2 Adiabatic compression → $\frac{\dot{W}_{in}}{\dot{m}} = (h_2 - h_1)$

2 → 3 Heat addition → $\frac{\dot{Q}_{in}}{\dot{m}} = (h_3 - h_2)$

3 → 4 Adiabatic expansion → $\frac{\dot{W}_{out}}{\dot{m}} = (h_3 - h_4)$

4 → 1 Heat removal → $\frac{\dot{Q}_{out}}{\dot{m}} = (h_4 - h_1)$

Cycle Thermal Efficiency:

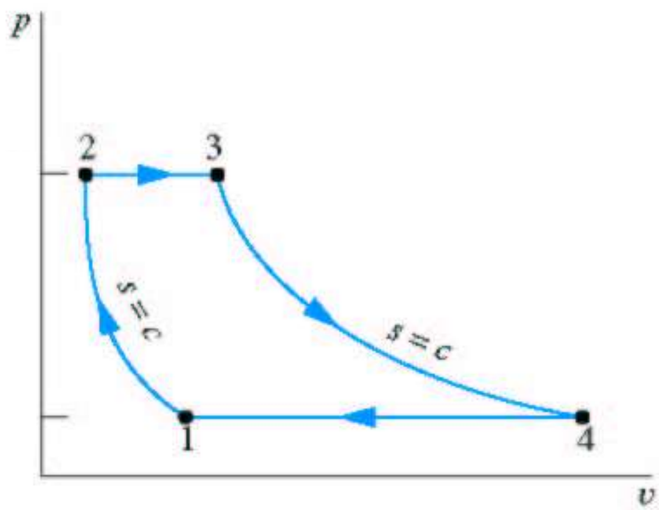
$$\eta_{\substack{Brayton\\cycle}} = 1 - \frac{\dot{Q}_{out}/\dot{m}}{\dot{Q}_{in}/\dot{m}} = 1 - \frac{h_4 - h_1}{h_3 - h_2}$$

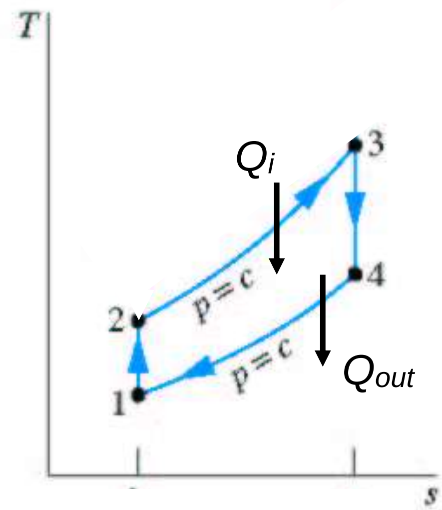
Back work ratio:

$$bwr = \frac{\dot{W}_{in}/\dot{m}}{\dot{W}_{out}/\dot{m}} = \frac{h_2 - h_1}{h_3 - h_4}$$

Ideal Air-standard Brayton Cycle (processes are reversible)

1 → 2 Isentropic compression
2 → 3 Constant pressure heat addition
3 → 4 Isentropic expansion
4 → 1 Constant pressure heat removal





For the isentropic process 1→ 2 $$P_{r2} = P_{r1}\left(\frac{P_2}{P_1}\right)$$

For the isentropic process 3 → 4 $$P_{r4} = P_{r3}\left(\frac{P_4}{P_3}\right)$$

Ideal Cold Air-standard Brayton Cycle

For isentropic processes 1 → 2 and 3 → 4

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \quad \text{and} \quad \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}}$$

Since $\frac{P_2}{P_1} = \frac{P_3}{P_4}$ thus $\left(\frac{T_2}{T_1}\right)^{\frac{k}{k-1}} = \left(\frac{T_3}{T_4}\right)^{\frac{k}{k-1}} \rightarrow \boxed{\frac{T_2}{T_1} = \frac{T_3}{T_4}}$

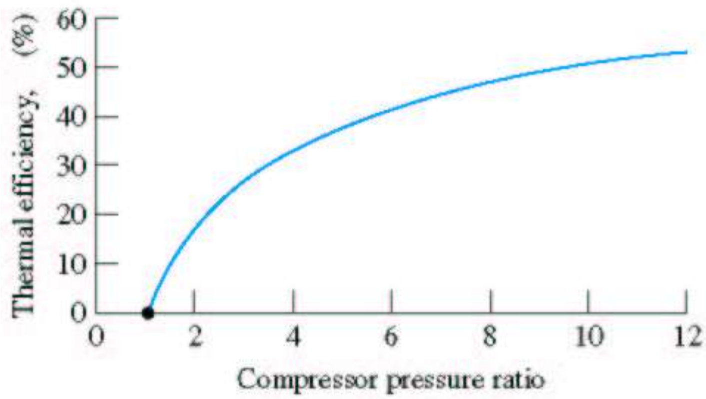
Thermal Efficiency

$$\eta_{\substack{Brayton\\constk}} = 1 - \frac{h_4 - h_1}{h_3 - h_2} = 1 - \frac{c_P(T_4 - T_1)}{c_P(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

recall $\frac{T_2}{T_1} = \frac{T_3}{T_4} \rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$

$$\boxed{\eta_{\substack{Brayton\\constk}} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{(P_2/P_1)^{\frac{k-1}{k}}}}$$

Efficiency increases with increased pressure ratio across the compressor



Back work ratio

$$bwr = \frac{\dot{W}_{in}/\dot{m}}{\dot{W}_{out}/\dot{m}} = \frac{\dot{W}_{comp}/\dot{m}}{\dot{W}_{turb}/\dot{m}} = \frac{c_P(T_2 - T_1)}{c_P(T_3 - T_4)} = \frac{T_2 - T_1}{T_3 - T_4}$$

Typical BWR for the Brayton cycle is 40 - 80% compared to < 5% for the Rankine cycle.

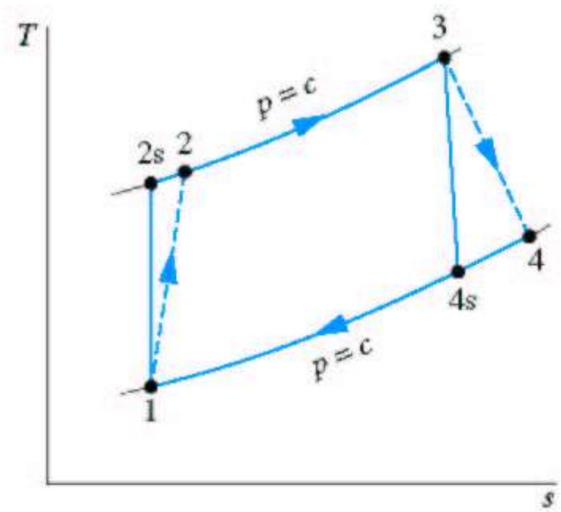
Recall, reversible compressor work is given by $\int_1^2 vdP$
Since gas has a much larger specific volume than liquid much more power is required to compress the gas from P_1 to P_2 in the Brayton cycle compared to the Rankine cycle for which liquid is compressed.

The turbine inlet temperature is limited by metallurgical factors, e.g., T_{max} = 1700K

Gas Turbine Irreversibilities

In the *ideal* Brayton cycle all 4 processes are assumed reversible, thus processes 2-3 and 4-1 are constant pressure and processes1-2 and 3-4 are isentropic.

The constant pressure assumption does not normally incur any great errors but the compressor and turbine processes are far from isentropic



Ideal (reversible) processes:
1 - 2s and 3 - 4s

Actual (irreversible) processes:
1 - 2 and 3 - 4

These irreversiblities are taken into account by:

$$\eta_{turb} = \frac{\left(\dot{W}_t / \dot{m}\right)}{\left(\dot{W}_t / \dot{m}\right)_s} = \frac{h_3 - h_4}{h_3 - h_{4s}} \qquad \eta_{comp} = \frac{\left(\dot{W}_c / \dot{m}\right)_s}{\left(\dot{W}_c / \dot{m}\right)} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

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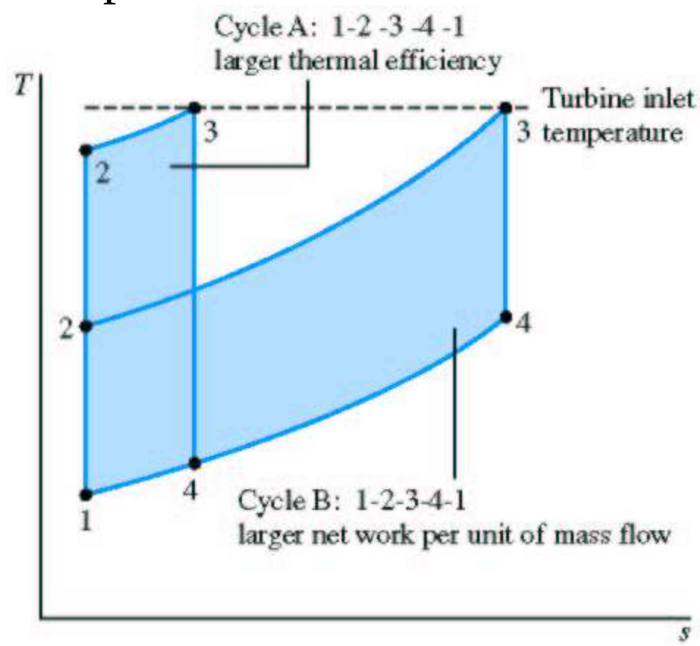
Efficiency versus Power

Consider two Brayton cycles A and B with a similar turbine inlet temperatures T_3



Since $\left(\frac{P_2}{P_1}\right)_A > \left(\frac{P_2}{P_1}\right)_B$ → $\eta_A > \eta_B$

Since (enclosed area 1-2-3-4)$_B$ > (enclosed area 1-2-3-4)$_A$

$$\left(\frac{\dot{W}_{cycle}}{\dot{m}}\right)_B > \left(\frac{\dot{W}_{cycle}}{\dot{m}}\right)_A \rightarrow \frac{\dot{m}_A}{\dot{m}_B} = \frac{\dot{W}_{cycle,A}}{\dot{W}_{cycle,B}}$$

In order for cycle A to produce the same amount of net power as cycle B, i.e., $\dot{W}_{cycle,A} = \dot{W}_{cycle,B}$, need $\dot{m}_A > \dot{m}_B$.

Higher mass flow rate requires larger (heavier) equipment which is a concern in transportation applications

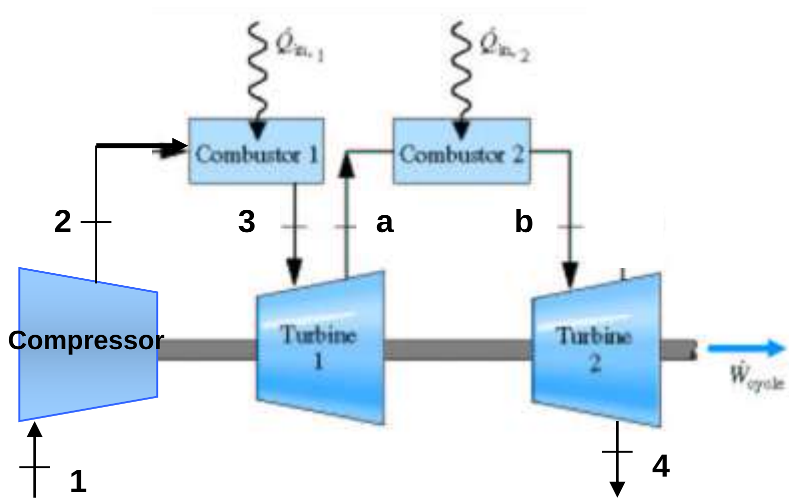
Increasing Cycle Power

The net cycle power is: $\dot{W}_{cycle} = \dot{W}_t - \dot{W}_c$

The cycle power can be increased by either increasing the turbine output power or decreasing the compressor input power.

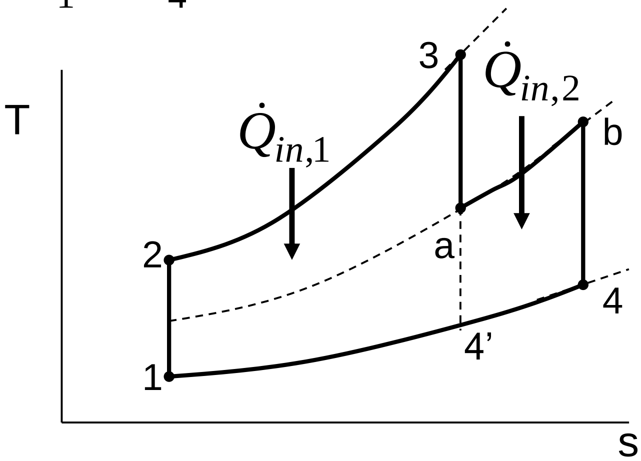
Gas Turbine with Reheat

The turbine work can be increased by using reheat, as was shown in the Rankine cycle



The turbine is split into two stages and a second combustor is added where additional heat can be added

Recall: $\frac{T_2}{T_1} = \frac{T_3}{T_{4'}}$ so, isobars on T-s diagram diverge



Note:
$h_b - h_4 > h_a - h_{4'}$

The total turbine work output *without* reheat is:

$$\dot{W}_{basic} = [(h_3 - h_a) + (h_a - h_{4'})]\dot{m}$$

The total turbine work output *with* reheat is:

$$\dot{W}_{\substack{turbine \\ w/reheat}} = \dot{W}_{t,1} + \dot{W}_{t,2} = [(h_3 - h_a) + (h_b - h_4)]\dot{m}$$

Since $h_b - h_4 > h_a - h_{4'}$ $\quad \dot{W}_{\substack{turbine \\ w/reheat}} > \dot{W}_{basic}$

Since the compressor work $h_2 - h_1$ is unaffected by reheat

$$\boxed{\dot{W}_{\substack{cycle \\ w/reheat}} > \dot{W}_{\substack{cycle \\ basic}}}$$

The reheat cycle efficiency is not necessarily higher since additional heat $\dot{Q}_{in,2}$ is added between states *a* and *b*

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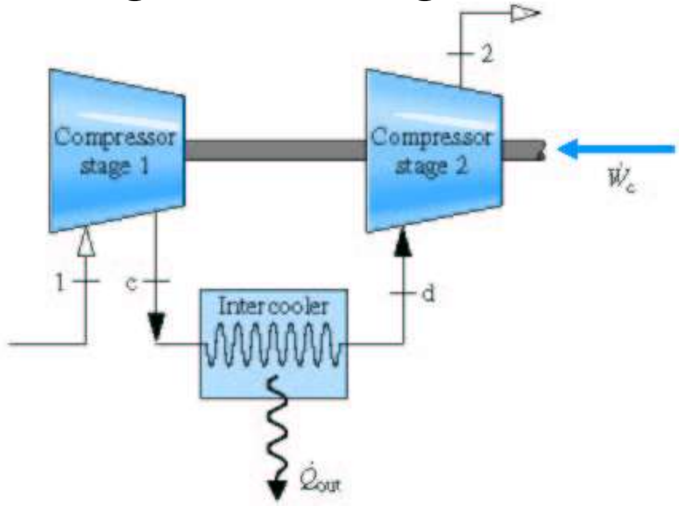
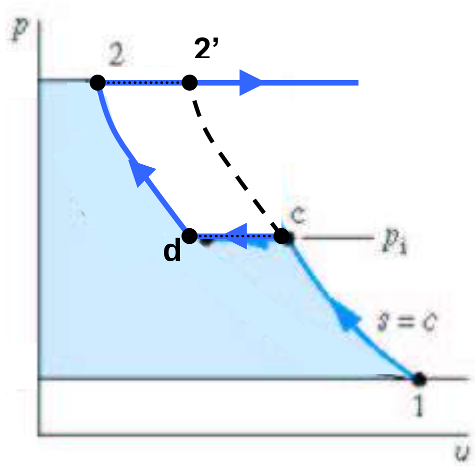
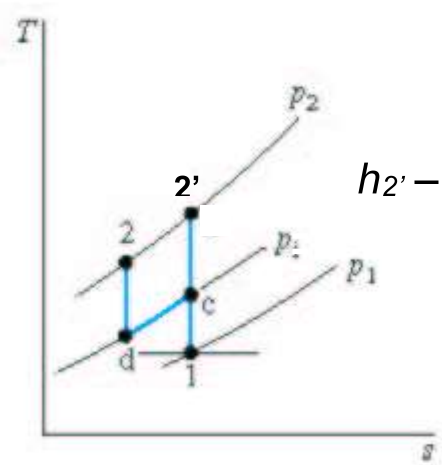
Compression with Intercooling

The compressor power can be reduced by compressing in stages with cooling between stages.



Recall: $\frac{T_2}{T_1} = \frac{T_3}{T_{4'}}$ so, isobars on T-s diagram diverge





$h_{2'} - h_c > h_2 -$

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The compressor power input *without* intercooling is:

$$\dot{W}_{basic} = \left[\left(h_{2'} - h_c\right) + \left(h_c - h_1\right)\right]\dot{m}$$

The total compressor power input *with* intercooling is:

$$\dot{W}_{\substack{comp \\ w/reheat}} = \dot{W}_{c,1} + \dot{W}_{c,2} = \left[\left(h_c - h_1\right) + \left(h_2 - h_d\right)\right]\dot{m}$$

Since $h_{2'} - h_c > h_2 - h_d$ → $\dot{W}_{\substack{comp \\ w/reheat}} < \dot{W}_{basic}$

Since the turbine work $h_3 - h_4$ is unaffected by intercooling

$$\boxed{\dot{W}_{\substack{cycle \\ w/reheat}} > \dot{W}_{\substack{cycle \\ basic}}}$$

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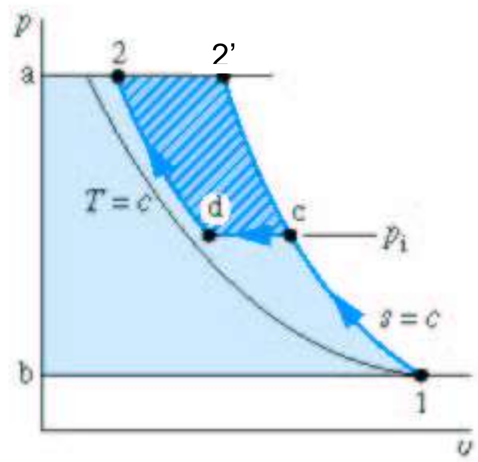
Different approach: The reversible work per unit mass for a steady flow device is $\int v dP$, so



Without intercooling : $$\left(\frac{\dot{W}_c}{\dot{m}}\right)_{basic} = \int_1^2 v dP = \int_1^c v dP + \int_c^{2'} v dP$$

$$= \text{area } b\text{-}1\text{-}c\text{-}2'\text{-}a$$

With intercooling : $$\left(\frac{\dot{W}_c}{\dot{m}}\right)_{w/\text{int}} = \int_1^2 v dP = \int_1^c v dP + \int_d^2 v dP$$

$$= \text{area } b\text{-}1\text{-}c\text{-}d\text{-}2\text{-}a$$

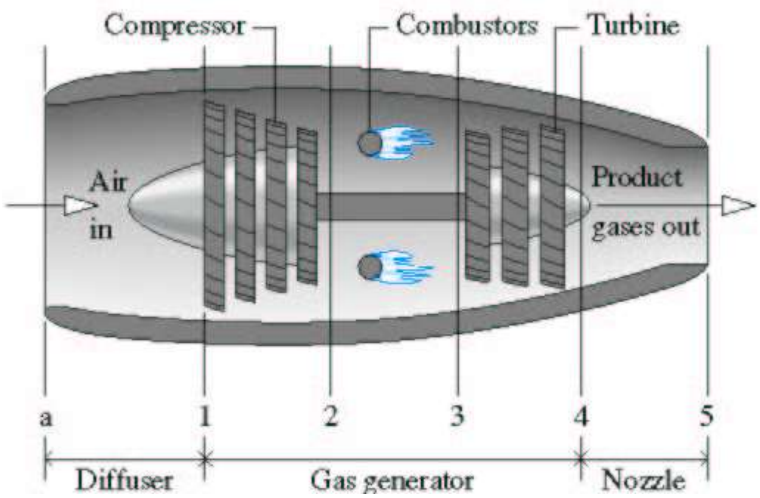
Since area(b-1-c-2'-a) > area(b-1-c-d-2-a)

$$\boxed{\left(\frac{\dot{W}_c}{\dot{m}}\right)_{basic} > \left(\frac{\dot{W}_c}{\dot{m}}\right)_{w/\text{int}}}$$

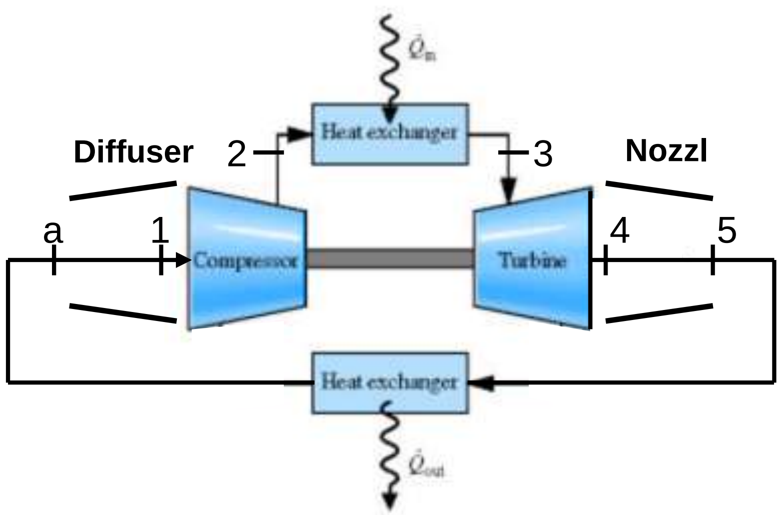
Aircraft Gas Turbines

Gas turbine engines are widely used to power aircraft because of their high power-to-weight ratio

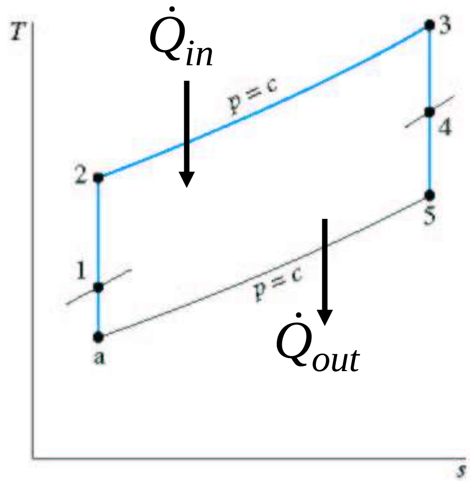
Turbojet engines used on most large commercial and military aircraft



Ideal air-standard jet propulsion cycle:



Normally compression through the diffuser (a-1), and expansion through the nozzle (4-5) are taken as isentropic



In the ideal jet propulsion engine the gas is not expanded to ambient pressure P_a.

Instead the gas expands to an intermediate pressure P_4 such that the power produced is just sufficient to drive the compressor, no net cycle power produced ($\dot{W}_{cycle} = 0$), thus

$$\frac{\dot{W}_c}{\dot{m}} = \frac{\dot{W}_t}{\dot{m}}$$

$$\boxed{(h_2 - h_1) = (h_3 - h_4)}$$

After the turbine the gas expands to ambient pressure P_5 which is the same as P_a.

Apply the steady-state conservation of energy equation to the Diffuser and Nozzle

$$0 = \frac{\cancel{\dot{Q}_{CV}}}{\dot{m}} - \frac{\cancel{\dot{W}_{CV}}}{\dot{m}} + \left(h_{in} + \frac{V_{in}^2}{2} \right) - \left(h_{out} + \frac{V_{out}^2}{2} \right)$$

Diffuser slows the flow to a zero velocity relative to the engine:

$$h_1 + \frac{\cancel{V_1^2}}{2} = h_a + \frac{V_a^2}{2}$$

Diffuser (a → 1)

$$\boxed{h_1 = h_a + \frac{V_a^2}{2}}$$

$$T_1 = T_a + \frac{V_a^2}{2c_P} \quad \text{for constant k}$$

Nozzle accelerates the gas leaving the turbine (turbine exit velocity negligible compared to nozzle exit velocity):

$$h_4 + \frac{\cancel{V_4^2}}{2} = h_5 + \frac{V_5^2}{2}$$

Nozzle (4 → 5)

$$\boxed{V_5 = \sqrt{2(h_4 - h_5)}}$$

$$V_5 = \sqrt{2c_P(T_4 - T_5)} \quad \text{for constant k}$$

The gas velocity leaving the nozzle is much higher than the velocity of the gas entering the diffuser, this change in momentum produces a propulsive force, or **thrust** F_t

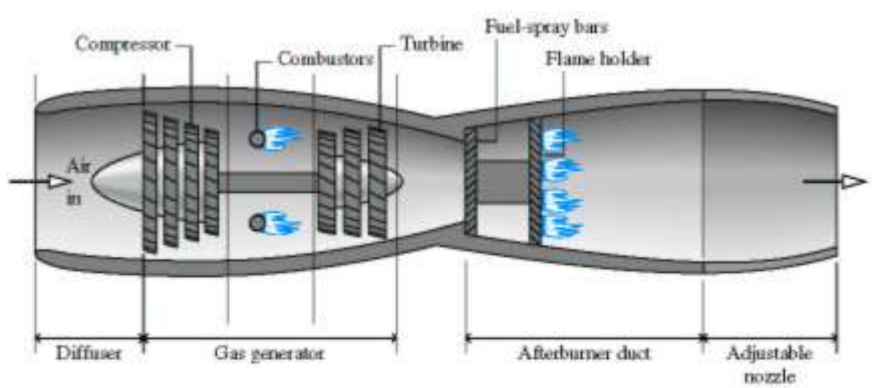
$$F_t = \dot{m}(V_5 - V_a)$$

Where V is flow velocity relative to engine

For aircraft under cruise conditions the thrust just overcomes the drag force on the aircraft → fly at high altitude where the air is thinner and thus less drag

To accelerate the aircraft increase thrust by increasing V_5

In military aircraft **afterburners** are used to get very large thrust for short take-offs on aircraft carriers



An afterburner is simply a reheat device!

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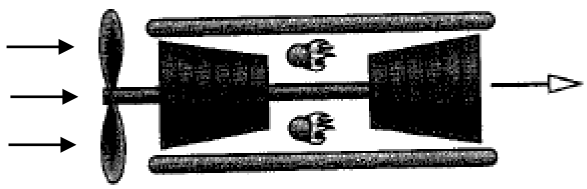
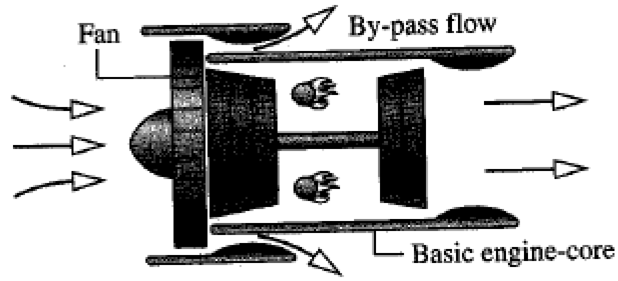
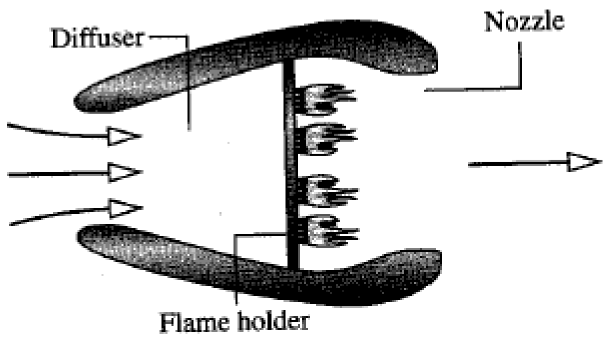
Other Propulsion Systems



Turboprop



Turbofan



Subsonic ramjet

In turbofan bypass flow produces additional thrust for take-off. During cruise thrust comes from turbojet

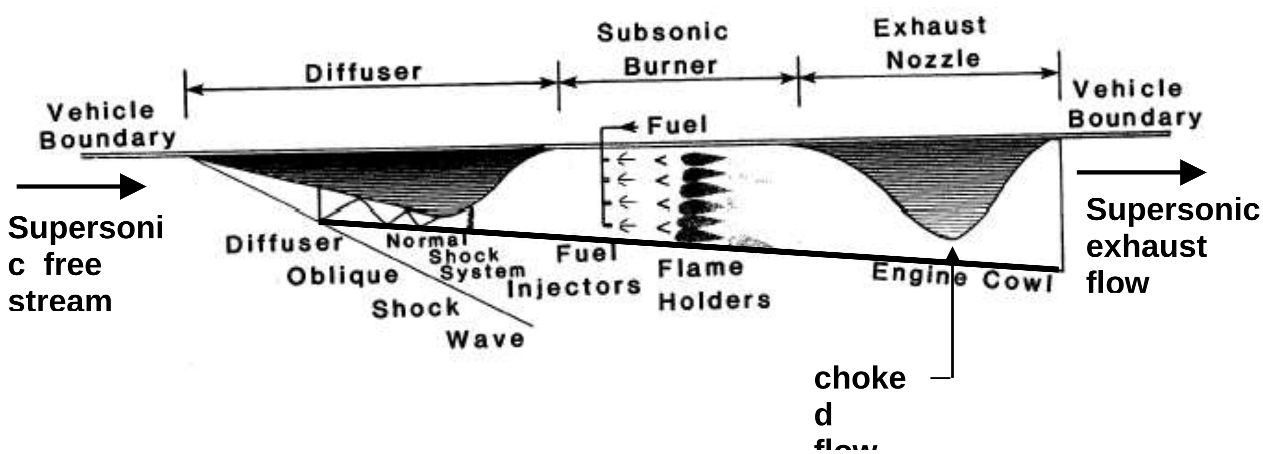
In a ramjet engine there is no compressor or turbine, compression is achieved gasdynamically.

Ramjet engines produce no thrust when stationary thus must be coupled with a turbojet engine to get off the ground

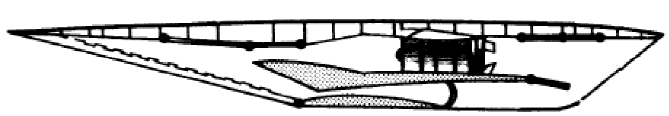
Supersonic Ramjet Engine

The flow is decelerated to subsonic velocity before the burner via a series of shock waves.

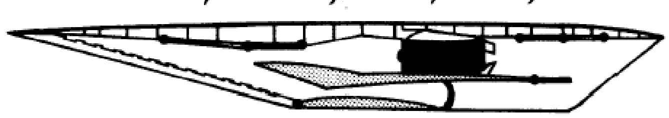
Combustion occurs at constant pressure



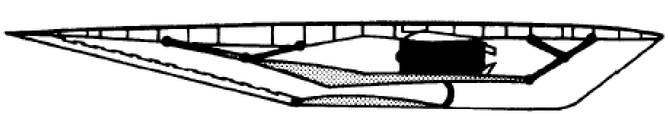
Turbojet-ramjet combination:



(a) Mach 0 to 0.9; Turbojet on, Ramjet cold flowing



(b) Mach 1 to 2.9; Dual mode



(c) Mach 3 to 5; Ramjet only

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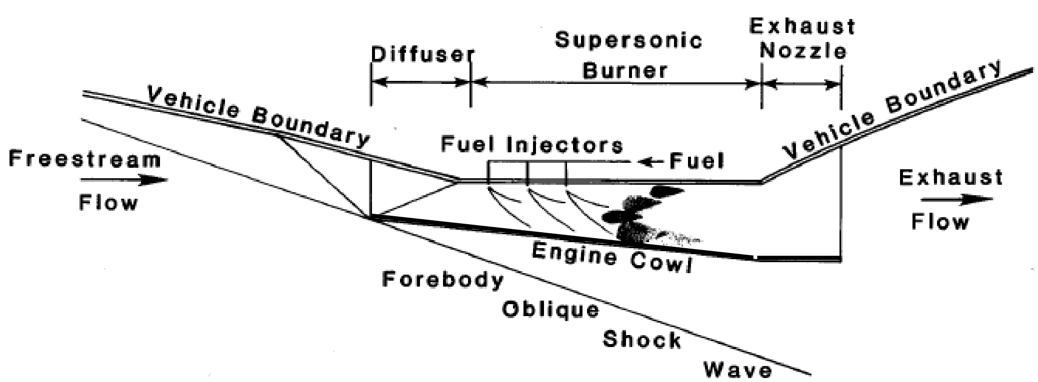
Supersonic Combustion Ramjet (SCRAMJET) Engine

At very high Mach numbers the air temperature gets extremely hot after deceleration through the diffuser

$$T_1 = T_a + \frac{V_a^2}{2c_P}$$

For Mach 6 flight speed, the air temperature just before the burner reaches about 1550K. At this temperature the air dissociates resulting in a drop in enthalpy

At flight speeds greater than Mach 6 (hypersonic) better to burn fuel- in supersonic air stream



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US National Aero Space Plane (X-30)

Was to use 5 scramjet engines to achieve a Mach 12 flight speed

To be used for travel to space and also as an airliner, a flight between any two points on earth would take less than 2 hours

Canceled in 1993!

Several countries have similar planes on the drawing board, Canada is not one of them!

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