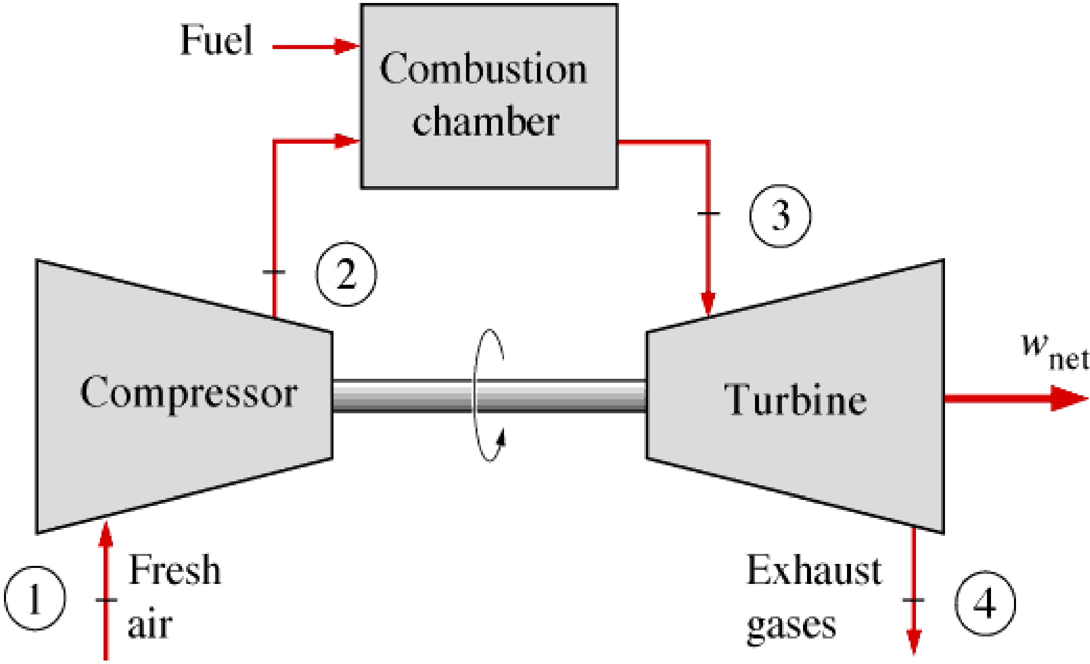
Gas Power Cycles (II)

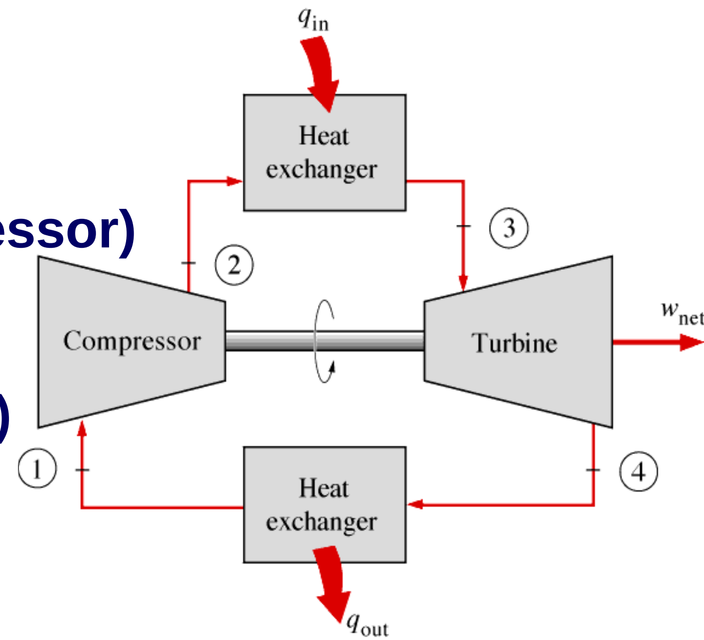
Actual Gas-Turbine Cycle

Fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised. The high-pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure. The resulting high-temperature gases then enter the turbine, where they expand to the atmospheric pressure, thus producing power. (An *open cycle*.)



8-7 Brayton Cycle:The Ideal Cycle for Gas-Turbine Engines

The open gas-turbine cycle *can be modeled* as a closed cycle, as shown in the figure below, by utilizing the air-standard assumptions.

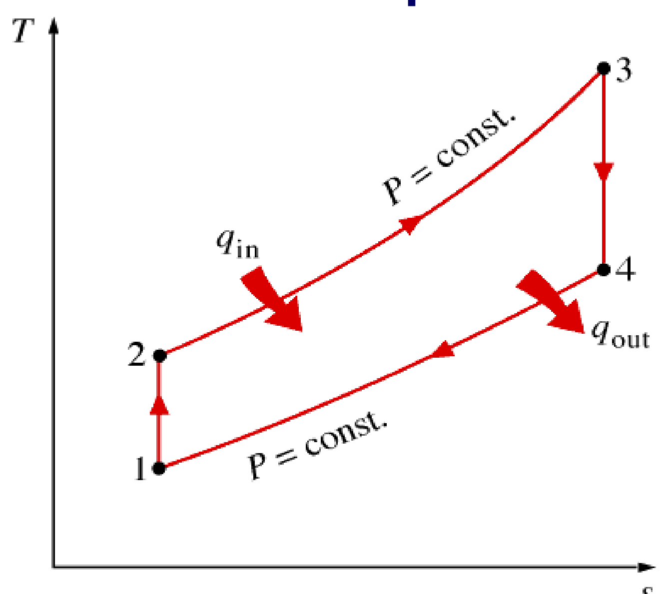


1→2 Isentropic compression (in a compressor)

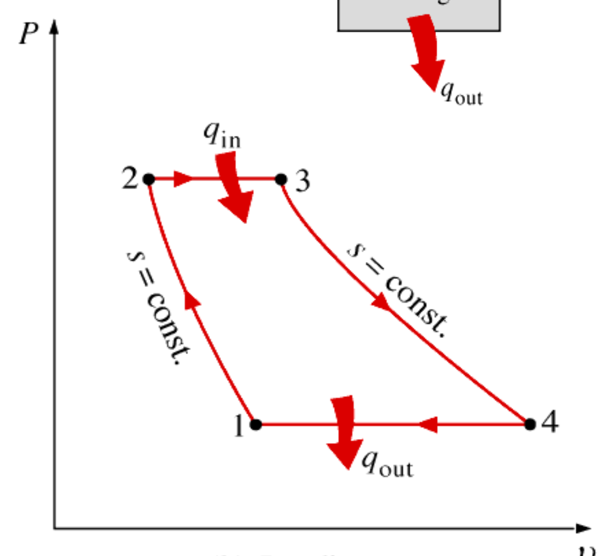
2→3 Constant pressure heat addition

3→4 Isentropic expansion (in a turbine)

4→1 Constant pressure heat rejection



(a) *T*-*s* diagram



(b) *P*- υdiagram

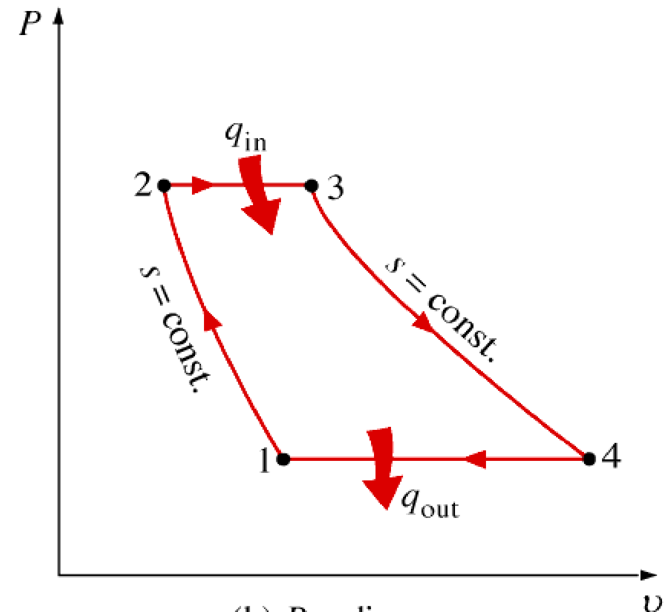
Thermal Efficiency of Ideal Brayton Cycle

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

$$q_{in} = h_3 - h_2 = C_p\left(T_3 - T_2\right)$$

$$q_{out} = h_4 - h_1 = C_p\left(T_4 - T_1\right)$$

$$= 1 - \frac{C_p\left(T_4 - T_1\right)}{C_p\left(T_3 - T_2\right)} = 1 - \frac{T_1\left(T_4/T_1 - 1\right)}{T_2\left(T_3/T_2 - 1\right)}$$



(b) *P*- υdiagram

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

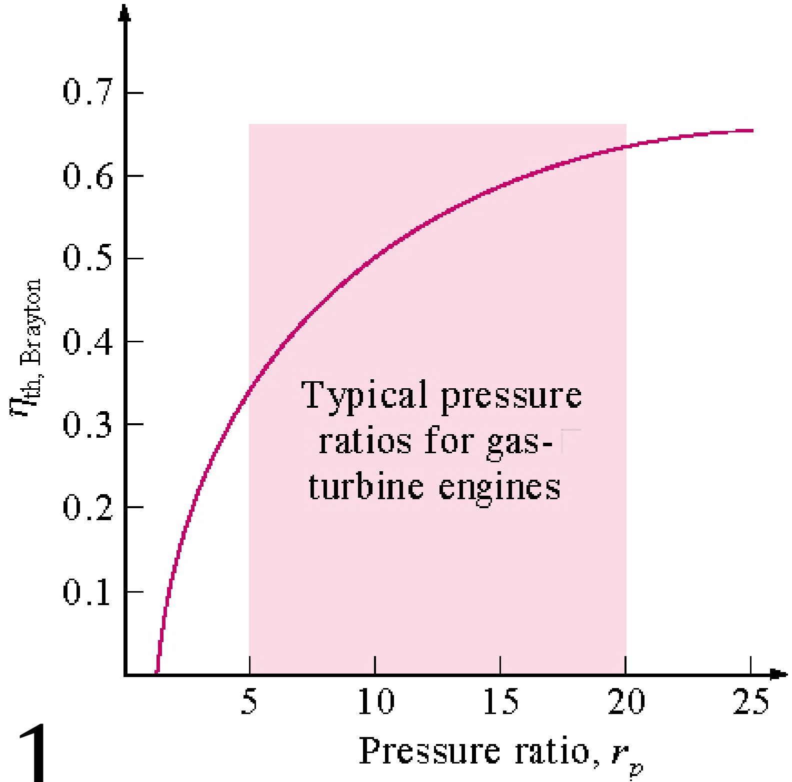
where $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$, and $r_p = \frac{P_2}{P_1}$ is the pressure ratio.

Thermal Efficiency of the Ideal Brayton Cycle

Under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle increases with:

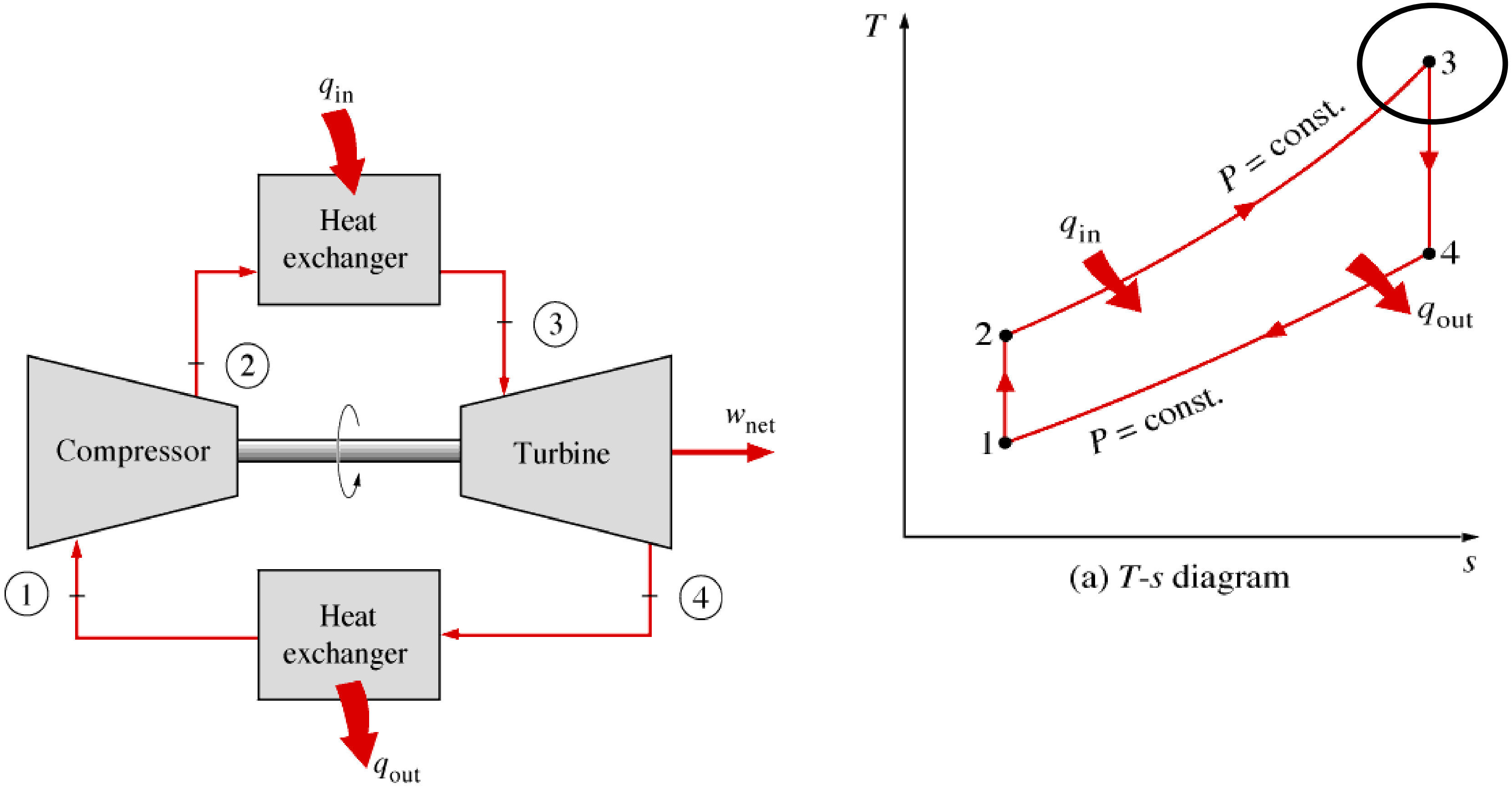
(1) the specific heat ratio, k

(2) the pressure ratio of the isentropic compression process.



$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

The highest temperature in the cycle occurs at the end of the combustion process, and it is limited by the *maximum temperature* that the turbine blades can withstand. This also *limits the pressure ratios* that can be used in the cycle.

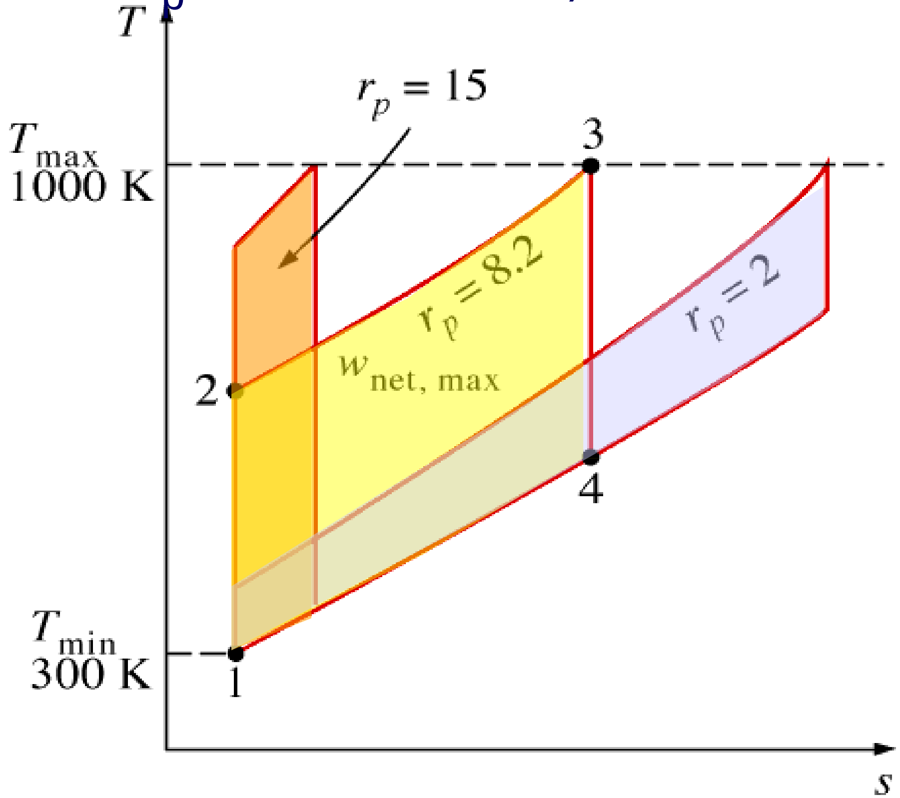


(a) T-s diagram

Net Work as a function of compression ratio

Now, suppose that our turbine blade can not tolerate more than 1000k (ie the turbine inlet temperature T3 should not exceed 1000k), then what would be the best compression ratio?

The figure below shows that the net work obtained at $r_p = 8.2$ is larger than the net work obtained at $r_p=2$. However, if we increase the rp further to rp=15, the wnet decreases again.This means that, there is an optimum compression ratio at which w_{net} maximum is obtained. In most common designs, the pressure ratio of gas turbines ranges from *about 11 to 16*.



Two major applications of Gas turbines

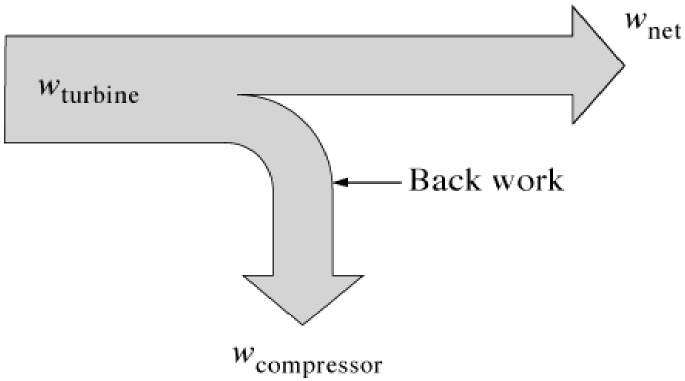
The two major application areas of gas-turbine engines are electric power generation and aircraft propulsion.

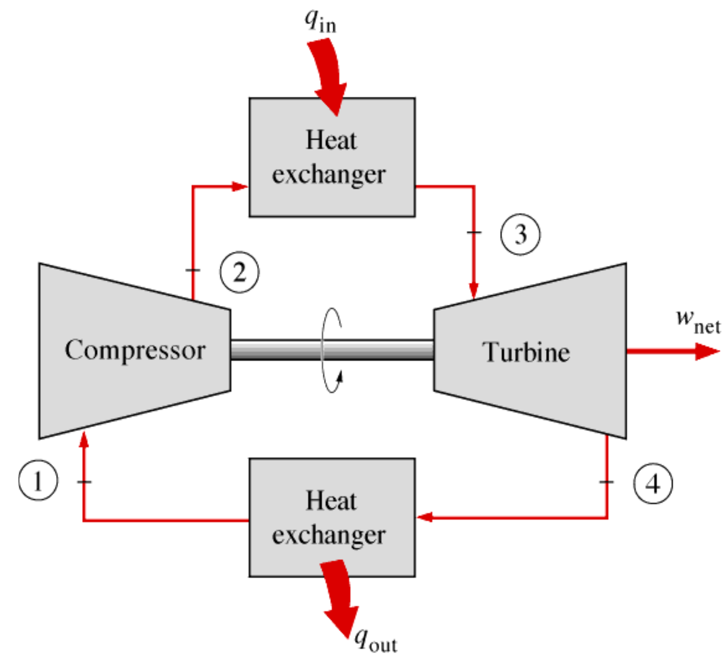
For electric power generation:

If we have steam turbine, diesel engine and a gas turbine all of the same size and weight, then the gas turbine offers the greatest power, long life and convenient operation. The start up time has been reduce from 4 hrs (in steam turbines) to 2 min for a gas turbine.

The construction costs of a gas turbine power plant are roughly half that of comparable steam power plant.

The Back Work Ratio





$$Back\ work\ \ ratio = \frac{w_{compr,in}}{w_{turb,out}}$$

Usually more than half of the turbine work output is used to drive the compressor.

$$w_{rev} = -\int_1^2 v dP$$

Therefore, the turbine used in gas-turbine power plants are larger than those used in steam power plants of the same net power output, P.

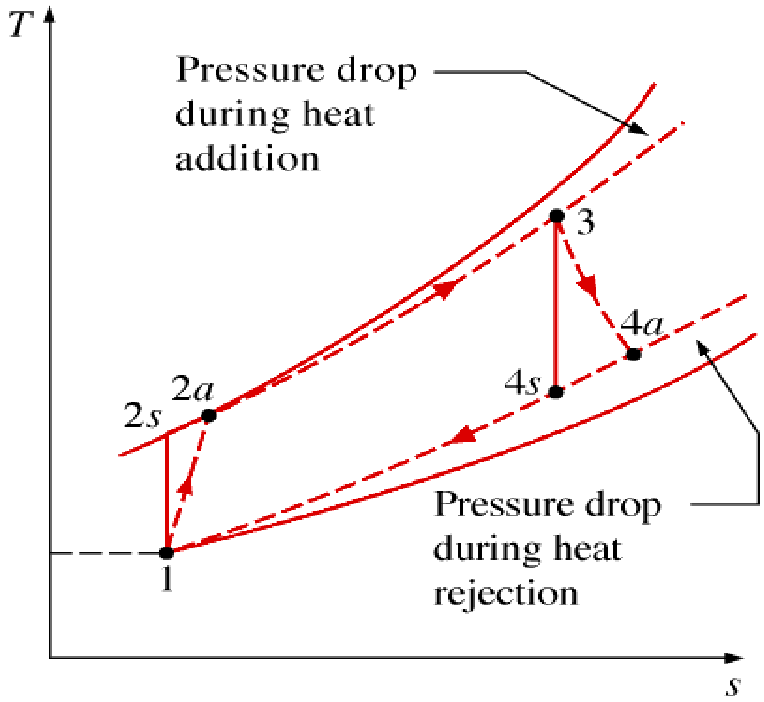
Development of Gas Turbines

The efforts to improve the cycle efficiency concentrated in three areas:

1. **Increasing the turbine inlet (or firing) temperature which can be achieve by the development of new materials and the innovative cooling techniques.**
2. **Increasing the efficiencies of turbo-machinery components by reducing aero-thermodynamic losses.**
3. **Adding modifications to the basic cycle such as incorporating inte-rcooling, regeneration, and reheating techniques.**

A more recent gas turbine manufactured by GE use 1425^{o}C turbine inlet temperature, 282 MW, and 39.5% efficiency in the simple-cycle mode.

Deviation of Actual Gas-Turbine Cycles from Idealized Ones



The deviation of actual compressor and turbine behavior from the idealized isentropic behavior can be accurately accounted for by utilizing the isentropic efficiencies of the turbine and compressor defined as (equations at bottom). Where states *2a* and *4a* are the actual exit states of the compressor and the turbine, respectively, and *2s* and *4s* are the corresponding states for isentropic case.

$$\eta_{isen,comp} = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \text{ and, } \eta_{turb,out} = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

Example

The Simple Ideal Brayton Cycle

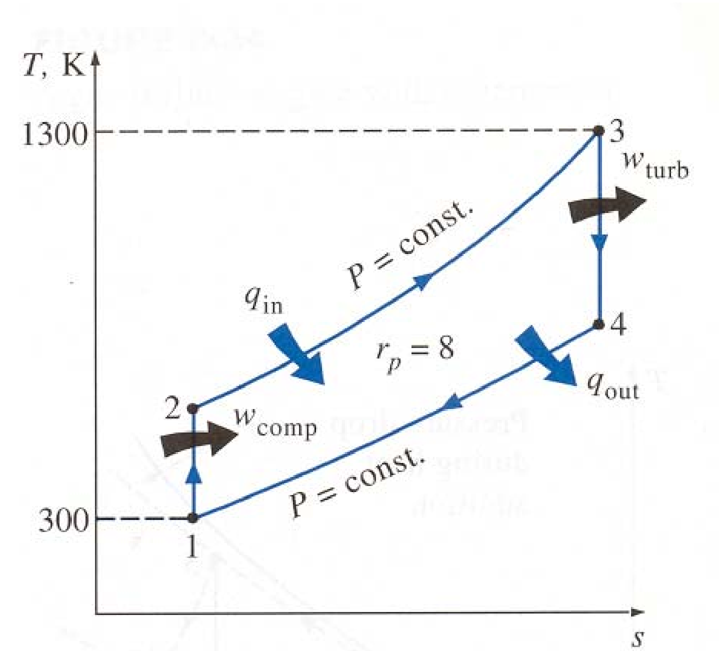
A stationary power plant operating on an ideal Brayton cycle has a pressure ratio of 8. The gas temperature is 300 K at the compressor inlet and 1300 K at the turbine inlet.

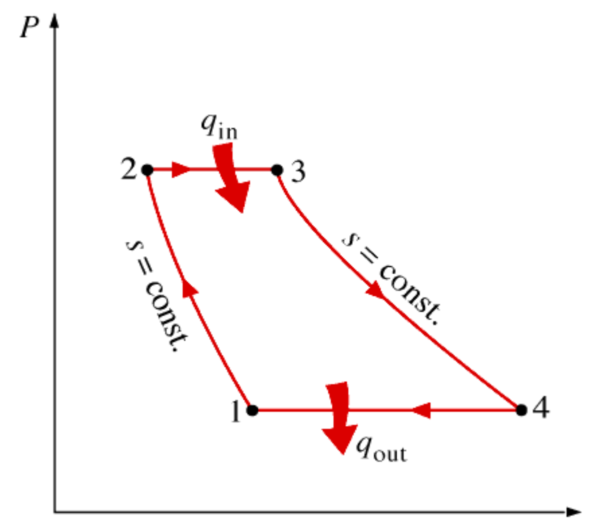
Utilizing the air-standard assumptions, determine

a) the gas temperature at the exit of the compressor and the turbine,

b) the back work ratio, and

c) the thermal efficiency.





(b) *P*- υdiagram

Example

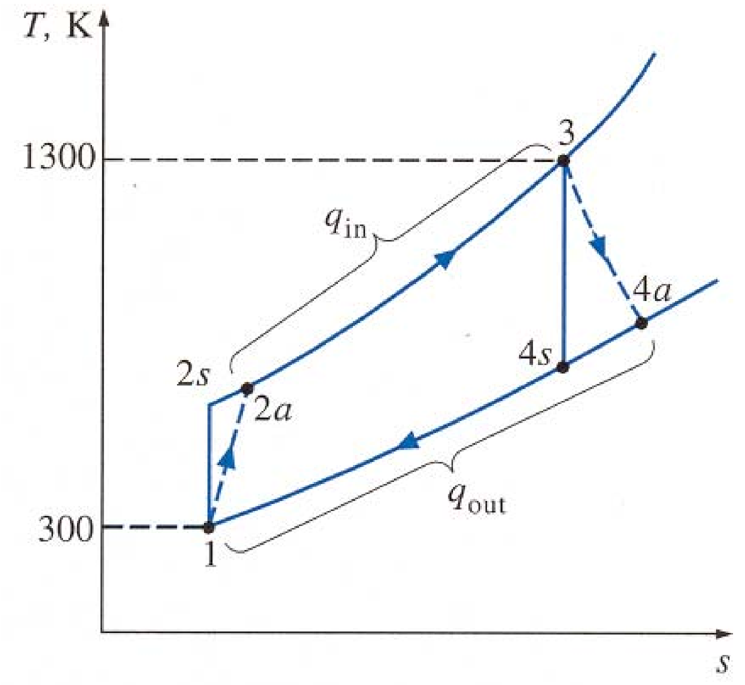
An Actual Gas-Turbine Cycle

Assuming a compressor efficiency of 80 percent and a turbine efficiency of 85 percent, determine

a) the back work ratio,

b) the thermal efficiency, and

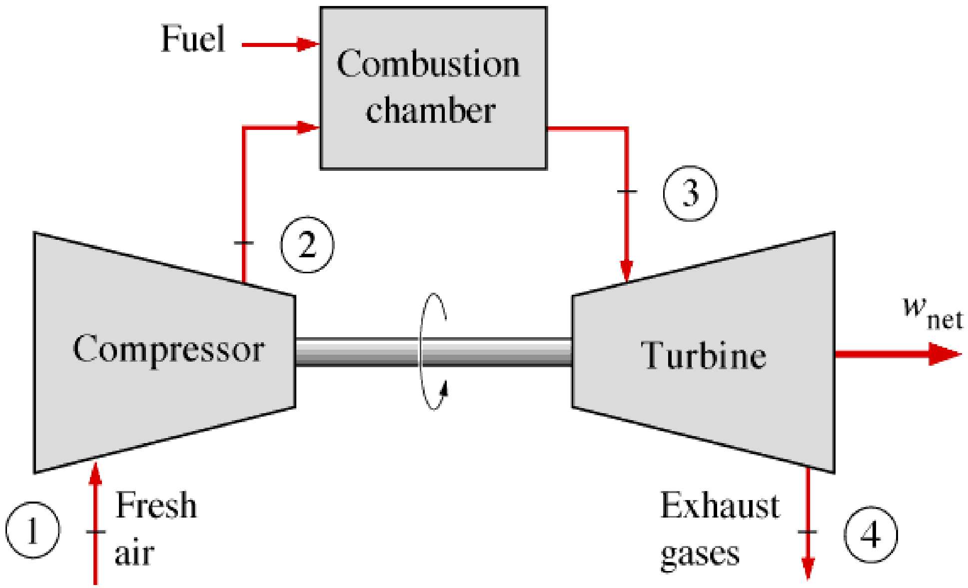
c) the turbine exit temperature of the gas-turbine power plant discussed in the example on previous Slide .

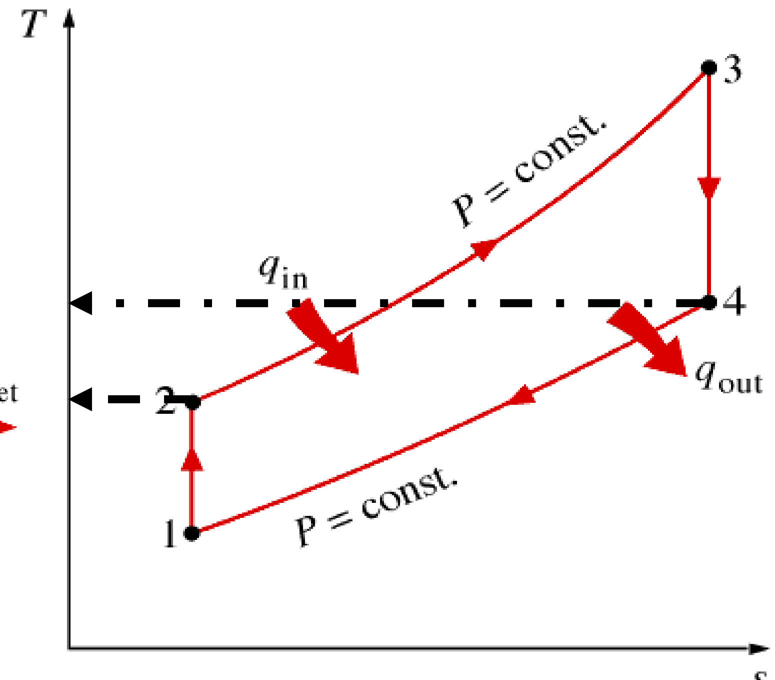


Solve on your own

8-8 The Brayton Cycle with Regeneration

Introduction



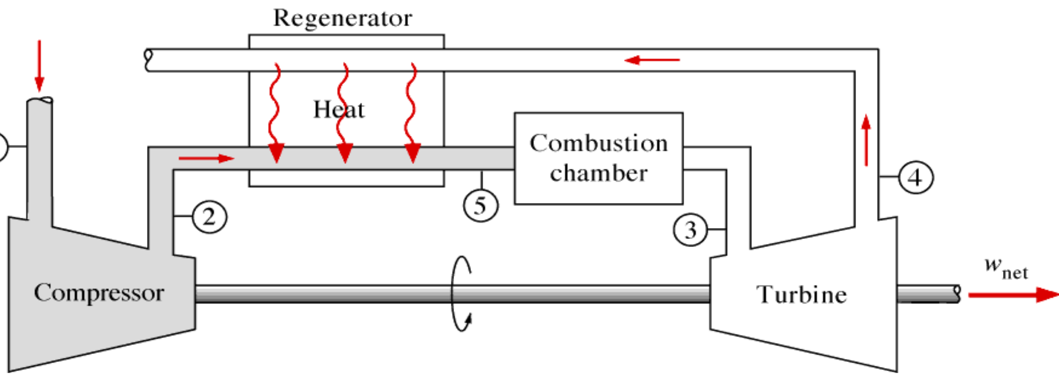


(a) *T*-*s* diagram

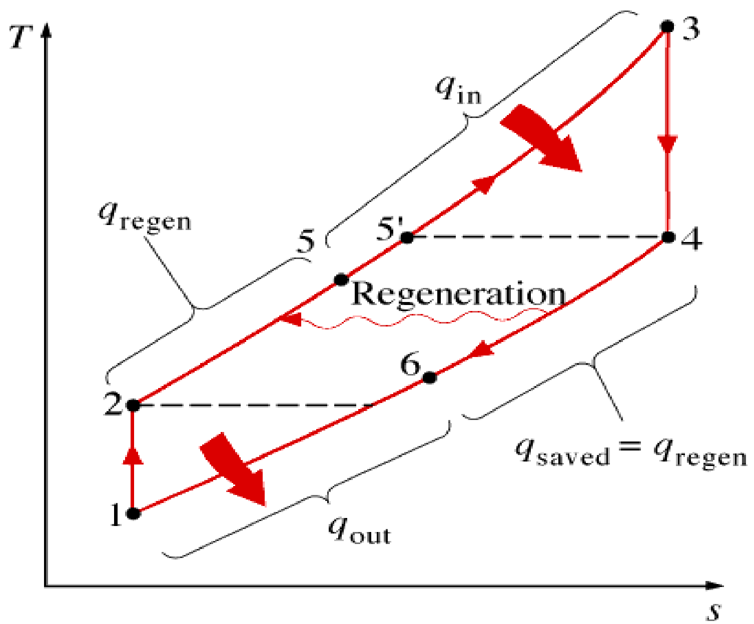
In gas-turbine engines, the temperature (T4) of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor (T2). Hence it would be wise to utilize the excess energy et point 4 to heat the compressed before entering the combustion chamber (heat exchanger in our model).

T-s Diagram of a Brayton Cycle with Regeneration

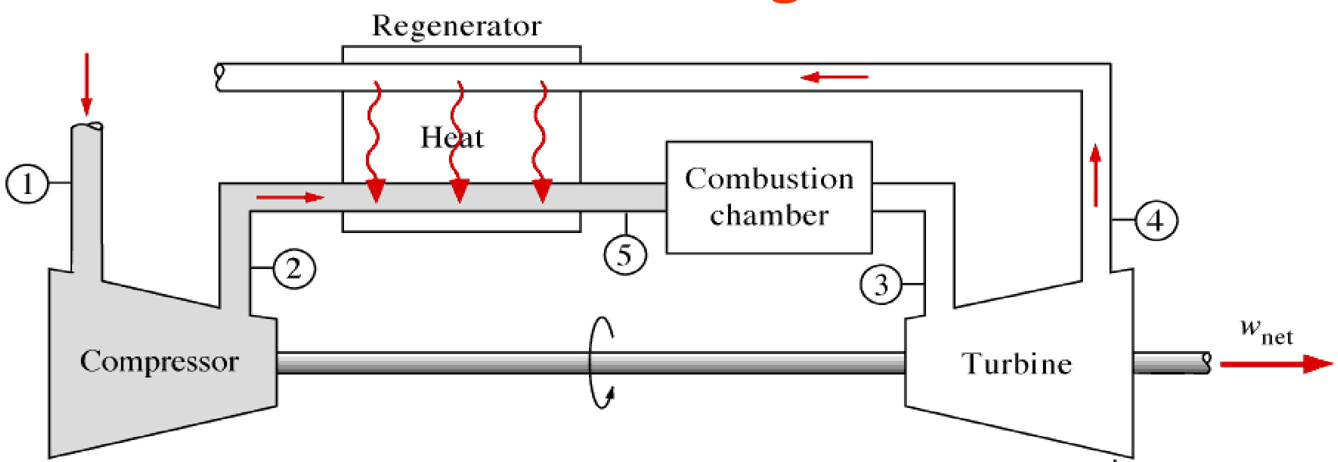
Therefore, the high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger,.



The thermal efficiency of the Brayton cycle increases as a result of regeneration since the portion of energy of the exhaust gases that is normally rejected to the surroundings is now used to preheat the air entering the combustion chamber.

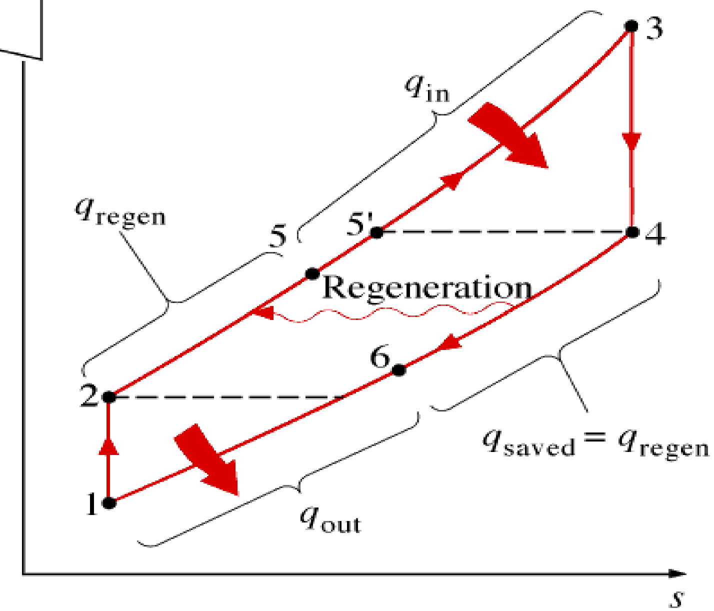


Effectiveness of the regenerator



$$\varepsilon = \frac{q_{regen,act}}{q_{regen,\max}} = \frac{h_5 - h_2}{h_4 - h_2}.$$

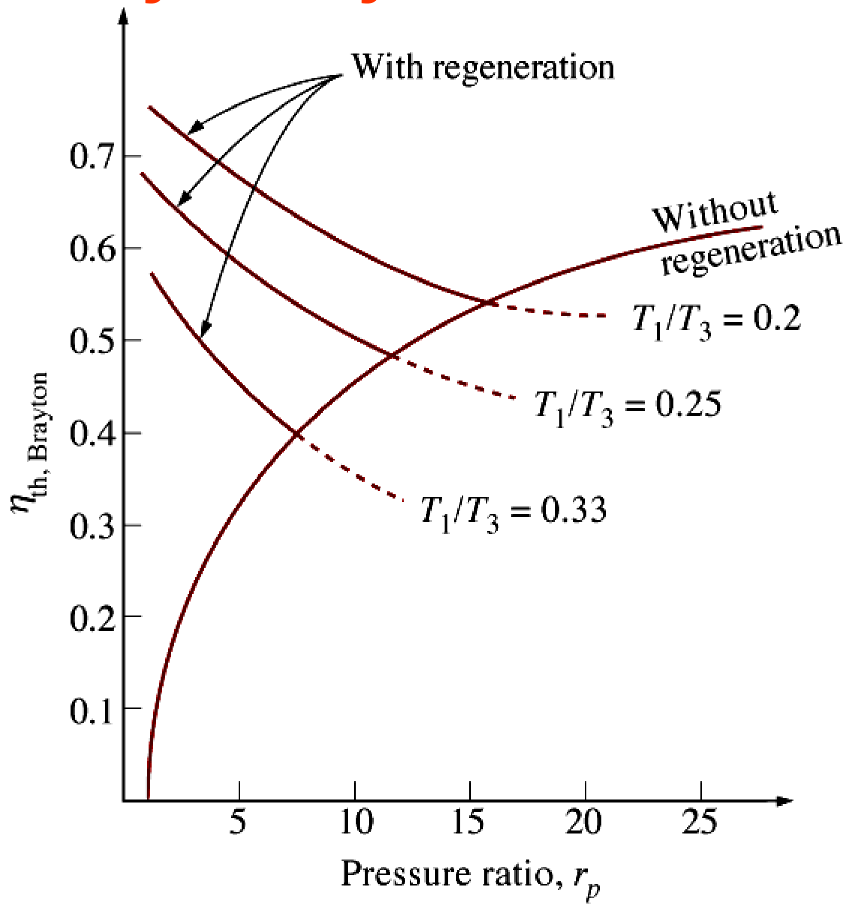
$$\varepsilon \cong \frac{T_5 - T_2}{T_4 - T_2}.$$



The use of a regenerator with a very high effectiveness (0.85 in practice) cannot be justified economically unless the savings from the fuel costs exceed the additional expense involved.

Thermal Efficiency of the Ideal Brayton Cycle with Regeneration

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(k-1)/k}$$



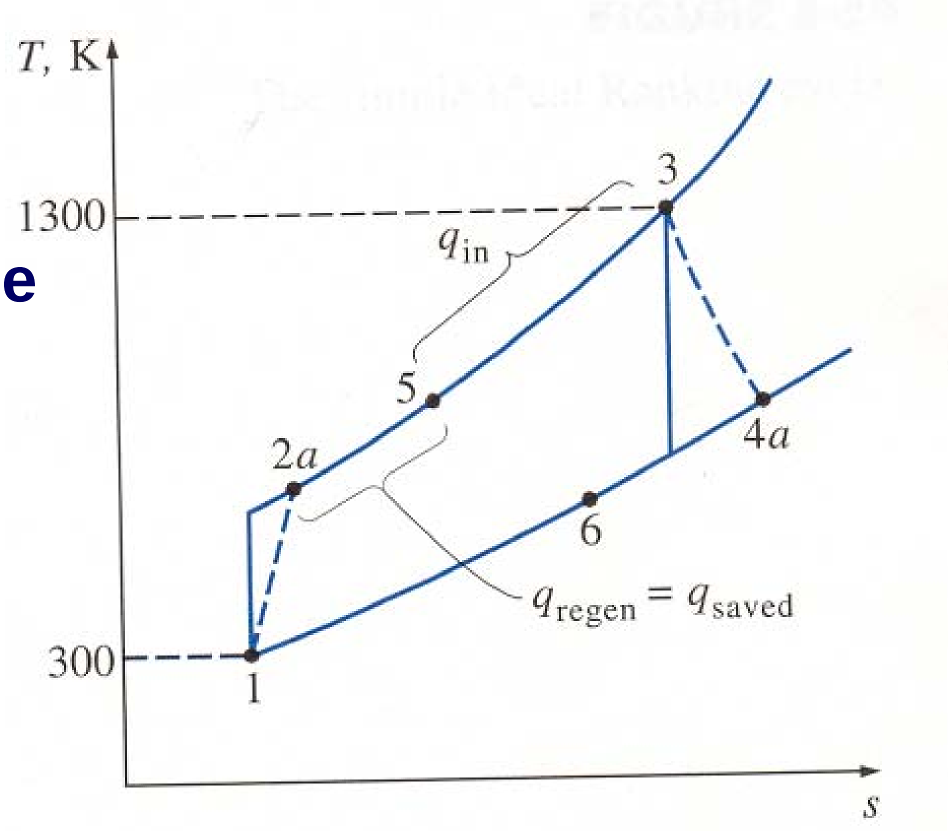
This means that the efficiency is function of: (1) The pressure ratio, (2) the specific heat ratio and (3) the ratio of the minimum to **maximum** temperature in the cycle.

The figure shows that regeneration is most effective at low pressure ratios and low minimum-to-maximum temperature ratios.

Example

Actual Gas-Turbine Cycle with Regeneration

Determine the thermal efficiency of the gas-turbine power plant described in the example on a previous slide if a regenerator having an effectiveness of 80 percent is installed.



Solve on your own

Ideal Gas-Turbine Cycle with Intercooling, Reheating, and Regeneration

The thermal efficiency of Bryton cycle can be further improved by reducing the compressor work, increasing the turbine work together with heat regeneration.

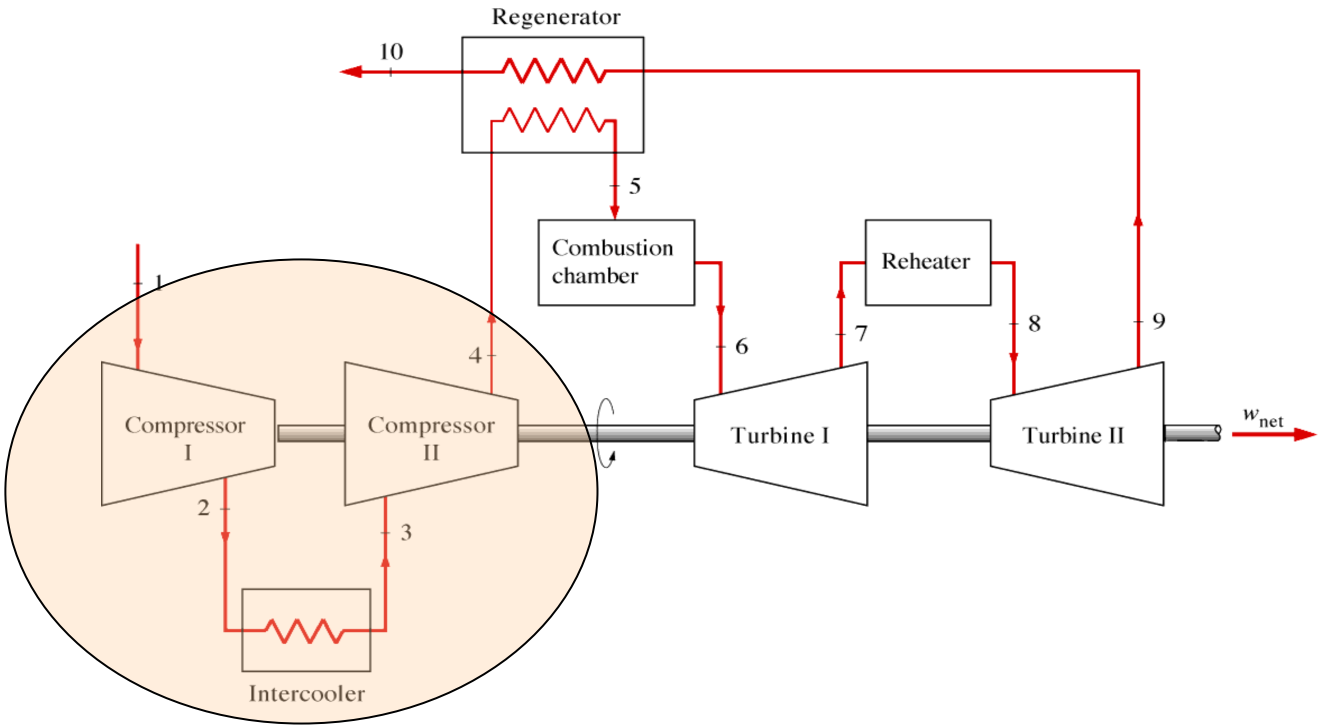
Recall from ME 203 that the w_{rev} for steady state devices was derived to be

$$w_{rev} = -\int_1^2 v\,dP$$

Hence the compressor work can be minimized by keeping v small (i.e. cooling the gas during the compression process).

The turbine work can be maximized by keeping v large (i.e. heating the gas during the expansion process).

How to minimize work input to a compressor

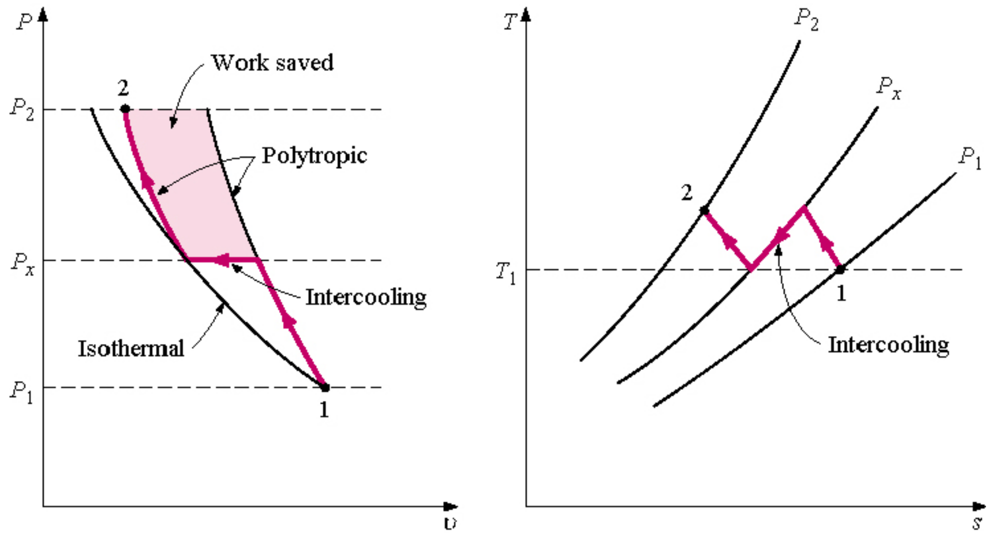


The figure above shows how this idea can be achieved. The compressor work is minimized by performing the compression process in two stages rather than one stage. This way we can cool the gas after the first stage though an inter-cooler. Then we compress again.

How to minimize work input to a compressor

The size of the colored area (the saved work input) on previous slide varies with the value of the intermediate pressure P_x.

The total work input for a two-stage compressor is the sum of the work inputs for each stage of compression.



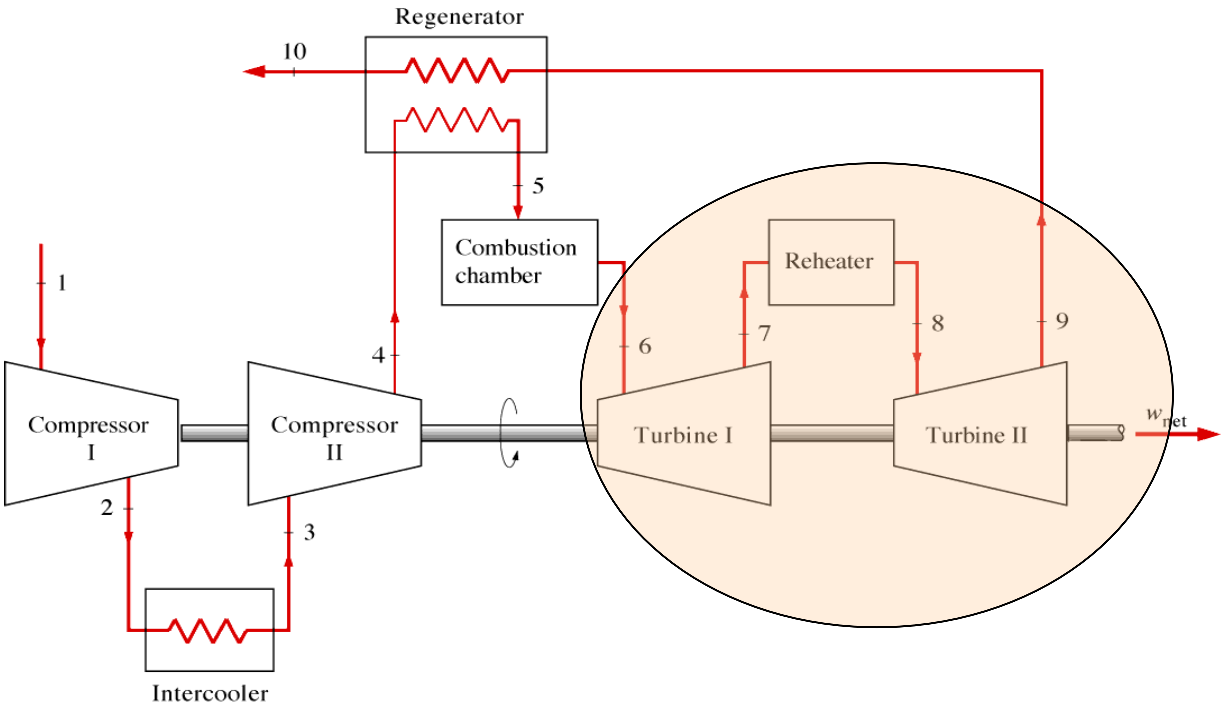
$$W_{comp,in} = W_{comp\,I,in} + W_{comp\,II,in} = \frac{nRT_1}{n-1}\left[\left(\frac{P_x}{P_1}\right)^{(n-1)/n} - 1\right] + \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_x}\right)^{(n-1)/n} - 1\right]$$

The only variable is P_x. The P_x value that will minimize the total work is determined by differentiating the above expression with respect to P_x. And setting the result to zero. This gives

$$\left(\frac{P_x}{P_1}\right) = \left(\frac{P_2}{P_x}\right) \Rightarrow P_x = \sqrt{P_1 P_2}$$

That is the compression ratio should be the same in each stage

How to maximize work output to a turbine

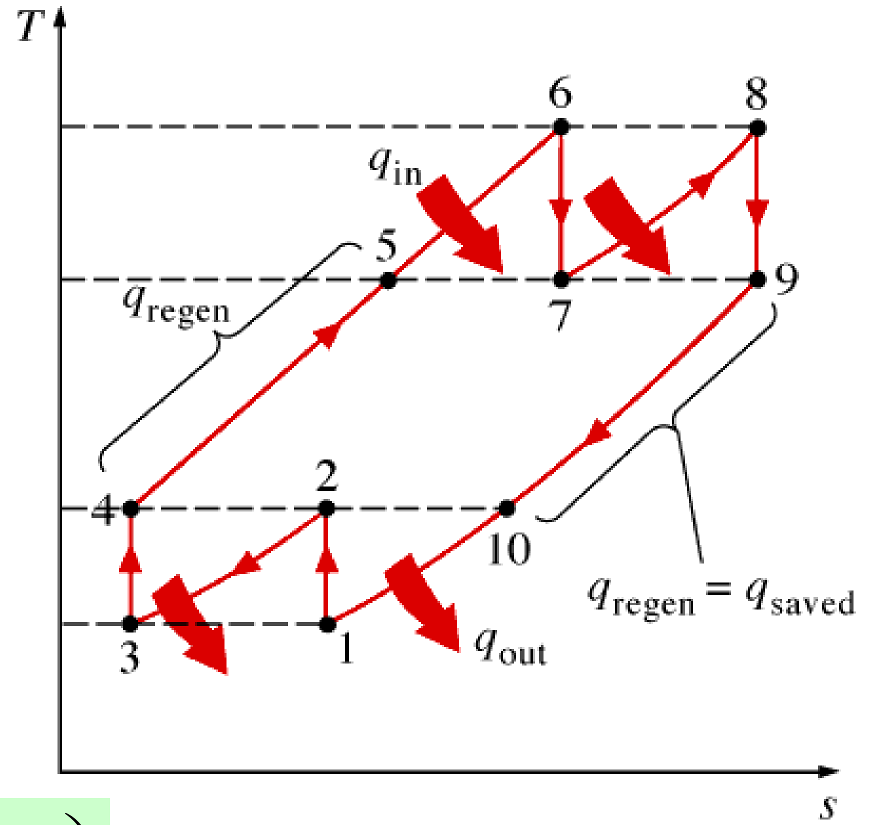


The figure above shows how this idea can be achieved. The turbine work is maximized by performing the expansion process in two stages rather than one stage. This way we can reheat the gas after the first stage though a reheater. Then we expand again. Similar to the compressor analysis, the expansion ratio should be the same in each stage.

T-s Diagram of Ideal Gas-Turbine Cycle with Intercooling, Reheating, and Regeneration

Note that the intercooling and reheating will always decrease the average temperature at which heat is added while reheating increase the temperature at which heat is rejected. This definitely reduce the efficiency of the Brayton cycle.

Therefore, regeneration should be used in conjunction with reheat and intercooling.

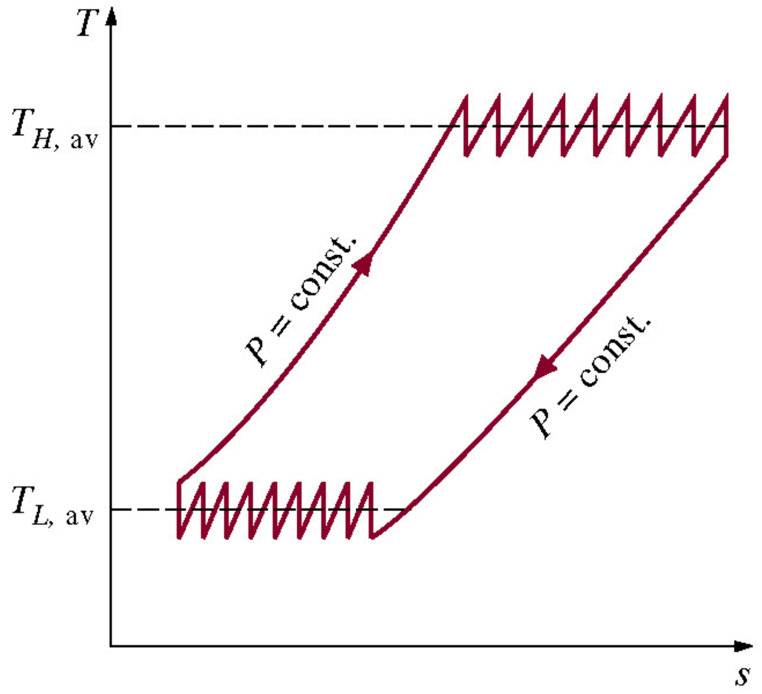


$$\left(\frac{P_2}{P_1}\right) = \left(\frac{P_4}{P_3}\right)$$

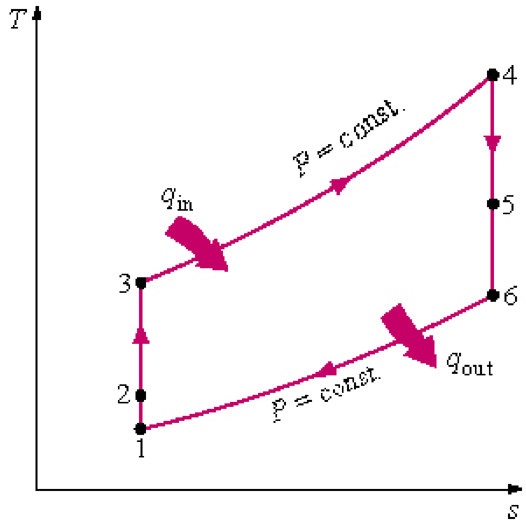
$$\left(\frac{P_6}{P_7}\right) = \left(\frac{P_8}{P_9}\right)$$

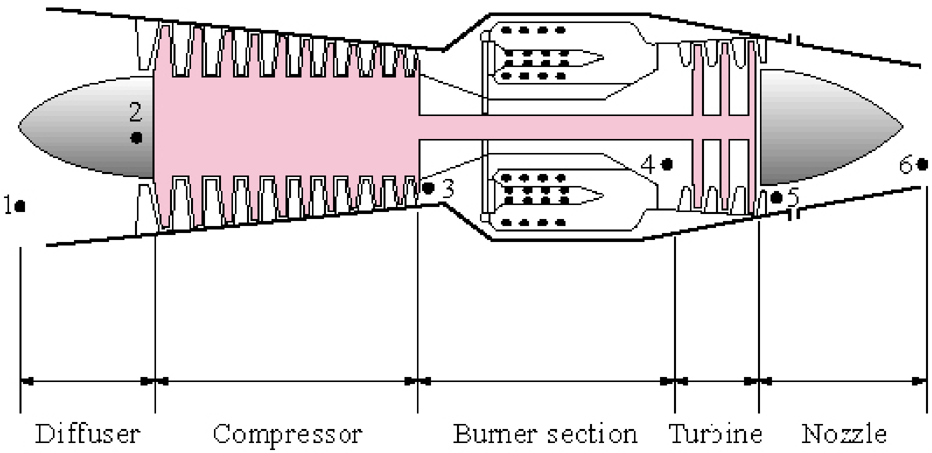
Approaching the Ericsson cycle.

As the number of compression and expansion stages increases, the gas-turbine cycle with intercooling, reheating, and regeneration approaches the Ericsson cycle.



Turbojet Engine Basic Components and *T*-*s* Diagram for Ideal Turbojet Cycle



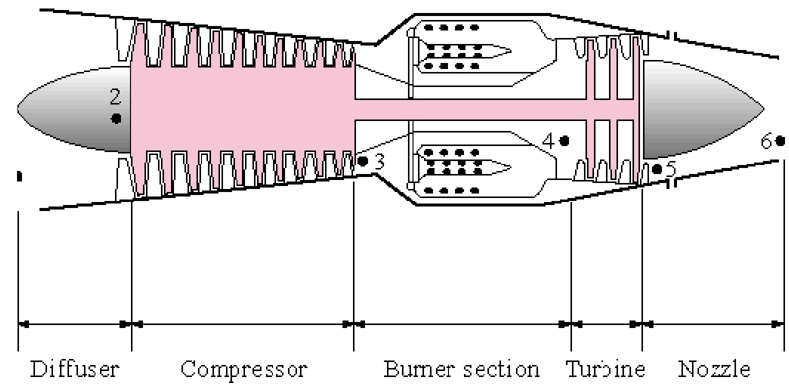


Gas-turbine engines are widely used to power aircraft because they are light and compact and have a high power-to-weight ratio.

The ideal jet-propulsion cycle differs from the simple ideal Brayton cycle in that the gases are partially expanded in the turbine. The gases that exit the turbine at a relatively high pressure are subsequently accelerated in a nozzle to provide the thrust needed to propel the aircraft.

Turbojet Engine

The ideal jet-propulsion differs from the simple ideal Bryton cycle in that the gases are not expanded to the ambient pressure in the turbine.



Instead, they are expanded to a pressure such that the power produced in the turbine is just sufficient to drive the compressor and the auxiliary components in the air plane. That is $w_{net} = 0$.

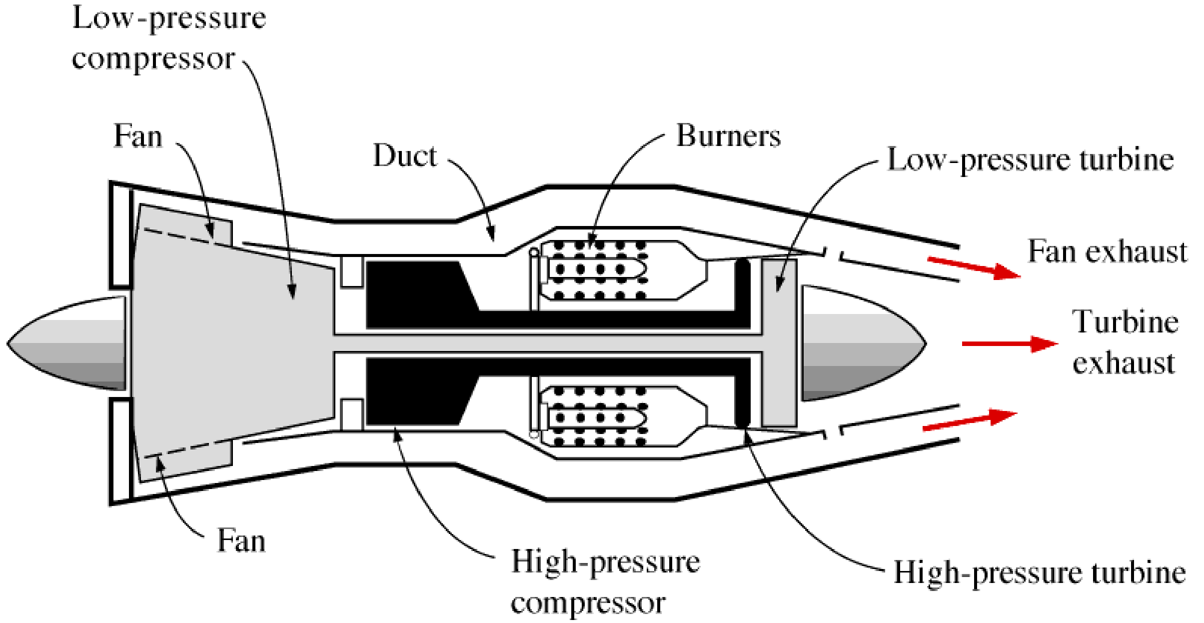
The gases that exit the turbine at a relatively high pressure are accelerated in a nozzle to provide the thrust to propel the aircraft.

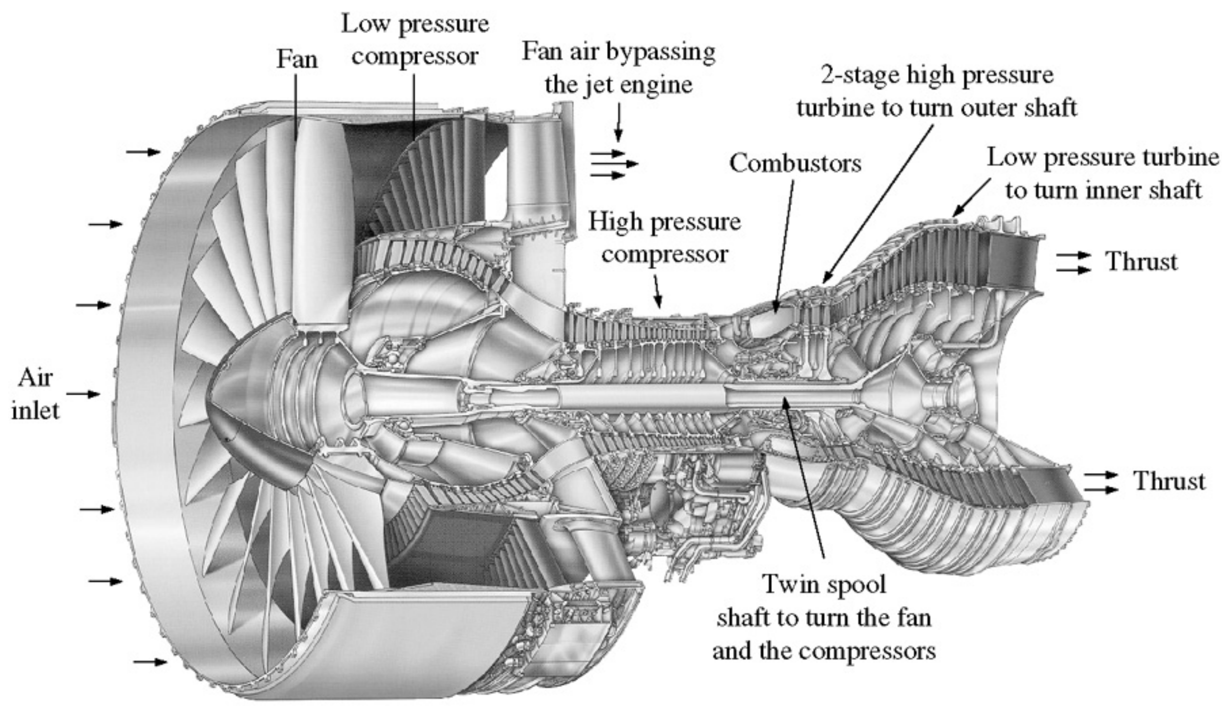
The net thrust developed by the turbojet engine is

$$F = \dot{m}\left(\vec{V}_{exit} - \vec{V}_{inlet}\right).$$

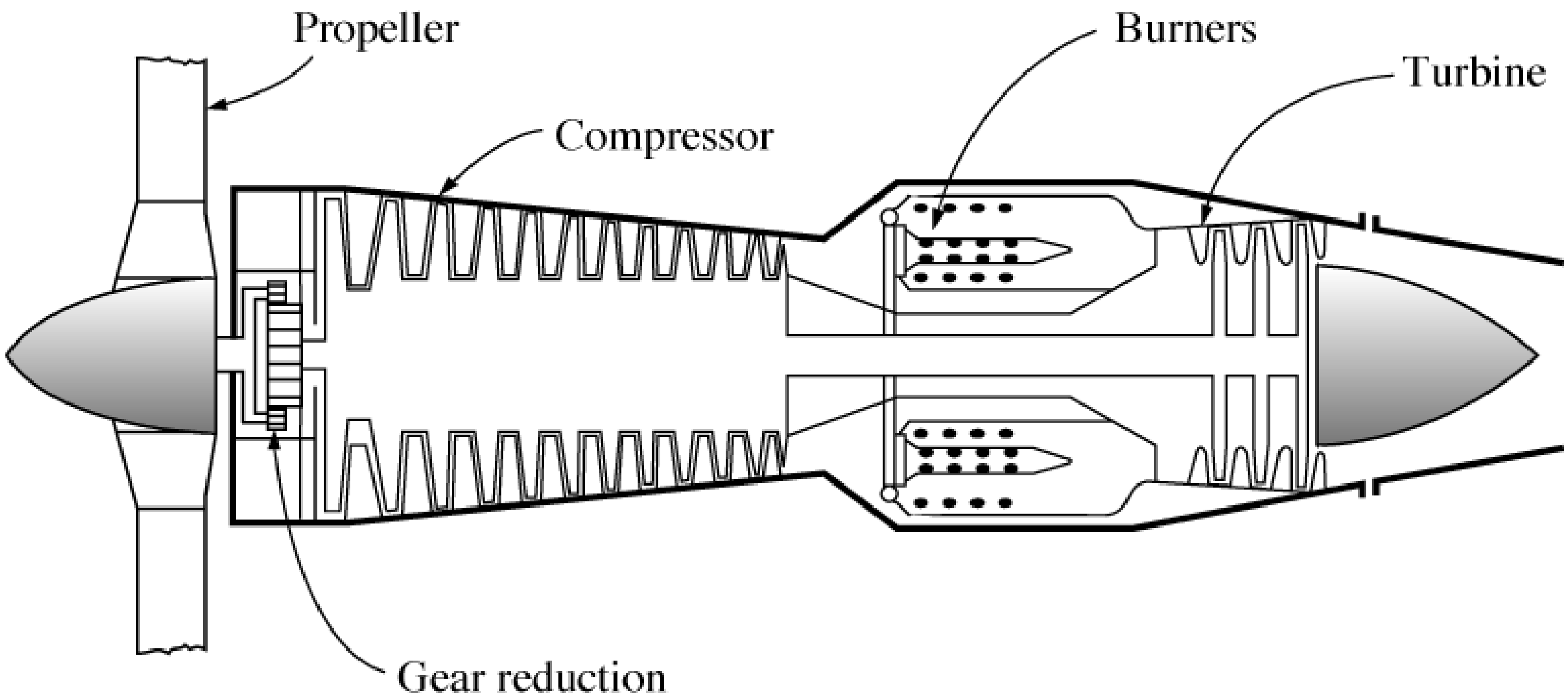
Turbofan Engine

The efficiency of the turbojet is low because of the large exit velocity. To increase the efficiency, the exit velocity is further decreases by extracting more energy in the turbine and use it to drive a fan without consuming additional fuel. This fan compress additional air part of which is passed to the engine core while the other part bypasses the jet engine resulting into additional thrust. A bypass ratio of 5 doubles the thrust and decreases the fuel consumption by 50% [Bathie pp 215].





Turboprop Engine



Thus it makes since to remove the cowl from the fan resulting in a bypass ratio of 100. We call this engine a turboprop engine. Its efficiency is larger than the efficiency of turboprop for low speed (up to 600 km/hr).

Second law analysis of gas power cycles

- Apply the law $X_d = T_o * S_g$
- Where $S_2 - S_1 = Q/T_b + S_g$
- But for a cycle $S_2 = S_1$
- Hence $S_g = -Q/T_b = -Q_H/T_H + Q_L/T_L$
- Hence $Xd = To*(-Q_H/T_H + Q_L/T_L)$
- Or $x_d = T_o(-q_H/T_H + q_L/T_L)$