

Applied Thermodynamics - II



Introduction

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Prerequisites

Thermodynamics

References

- Saravanamuttoo HH, Rogers GFC and Cohen H, *Gas Turbine Theory*, Fifth edition, Pearson, 2001.
- Ganesan V, *Gas Turbines*, Tata McGraw-Hill, 1999.

Class Timings

Tue: 3 PM to 4 PM, Room-106

Wed: 9 AM to 10 AM, Room-106

Thu: 9 AM to 10 AM, Room-106

Weblink: www.iitp.ac.in/~sudheer/teaching.html



Gas Power Cycles:

Introduction

Application

Different arrangements

Gas Power Cycles for Different Applications:

Shaft power cycles

Jet propulsion

Individual Components:

Compressors: centrifugal and axial-flow

Combustion chambers

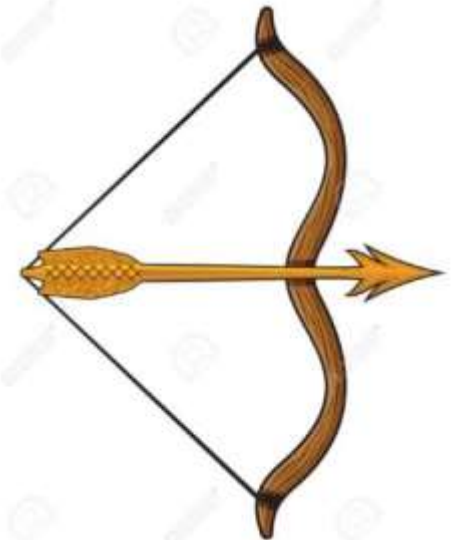
Turbines: axial and radial

Miscellaneous Topics

Prime Movers – Man's muscles



SEDAN CHAIRS.



Man learned to convert the heat of chemical reactions into mechanical energy.

Machines which server this purpose are known as **Heat Engines**.

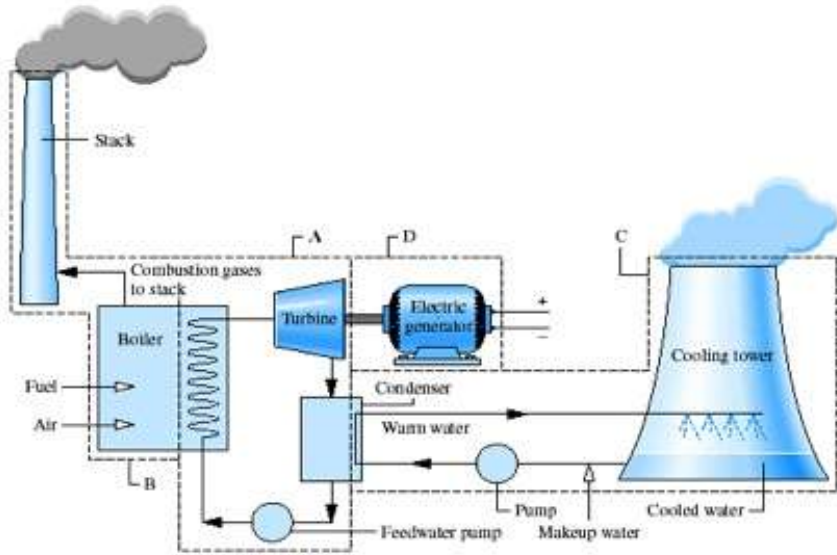
Chinese used fire lance in wars (10th Century).



Prime Movers – Modern day



Prime Movers – Modern day



Chrysler “Turbine” (1963) – turboshaft powered consumer vehicle.



Application of Thermodynamics

Important areas are **Power** generation and **Refrigeration**. Usually accomplished by systems that operate on a thermodynamic cycle.

Basing on output

Power cycles: Produce Mechanical work (power).

Refrigeration cycles: Produce Refrigeration effect.

Basing on phase of working fluid

Gas cycles: Working fluid remains in the gaseous phase.

Vapor cycles: Working fluid changes phase in the cycle.

Heat engine classification

Internal combustion: Fuel is burnt within the system boundaries.

External combustion: Heat is supplied to the working fluid from an external source such as furnace, nuclear reactor.



Usage

Started in 19th century

For power generation

Steam turbine plants producing 1000 MW of shaft power, $\eta = 40\%$

Widely used power plant for marine application

Still used in nuclear-powered aircraft carriers and submarines

Disadvantages

Need to produce high pressure, high temperature steam

Involves bulky, expensive steam generating equipment (boiler or nuclear reactor)

Hot gases doesn't directly interact with the turbine

Is it possible to bypass steam generation?

Directly impinging the hot gases on the turbine



How?

In order to produce an expansion through a turbine a pressure ratio must be provided

Hence compression of the working fluid is the first step

Initial unsuccessful attempts

Low efficiency of compressors at sufficiently high pressure ratio

Combustion temperature limitations imposed by the materials

Thanks to the development of Aerodynamics and Metallurgy

Pressure ratios of up to 35:1

Component efficiencies of 85-90%

Turbine inlet temperatures exceeding 1650 K



Advantages

Absence of reciprocating and rubbing members
reduces the vibration and balancing problems

High reliability and easy to maintain than a piston engine

Low lubricating oil consumption

High power to weight ratio

Compressor

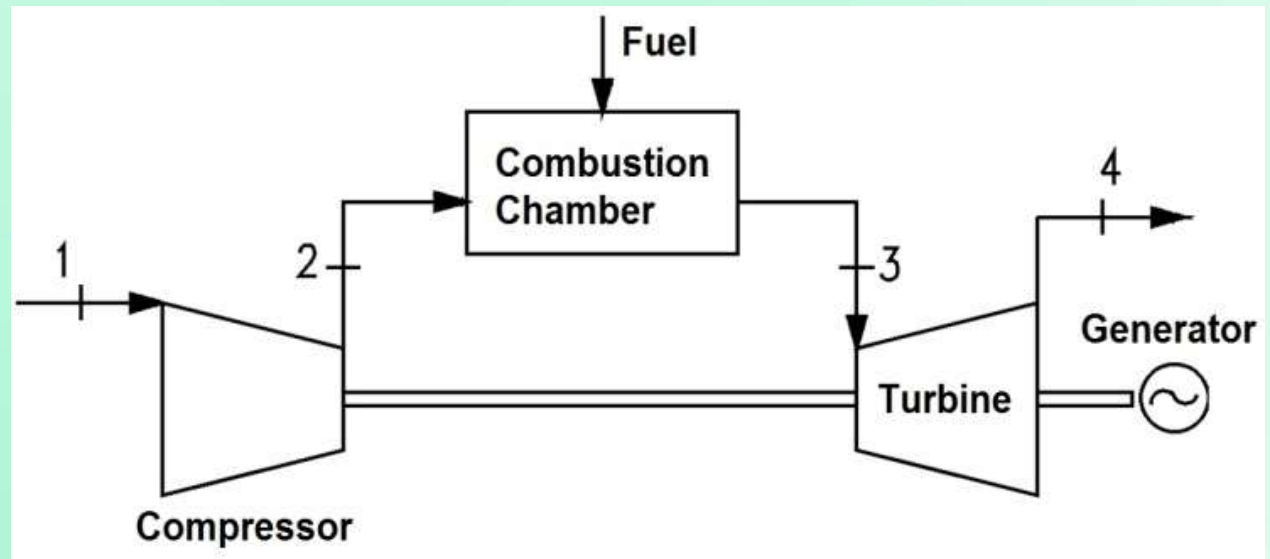
To produce expansion in turbine, pressure ratio is required

Combustion chamber

Working fluid (air) gets heated up

Turbine

Energy of the working fluid is converted into rotating energy of blades





- The process of compression, combustion and expansion do not occur in a single component as they do in a reciprocating engine.
- Hence, designed, tested and developed individually and these components can be linked together to form gas turbine unit in a variety of ways.
- Auxiliary devices:
 - Intercoolers between the compressors
 - Reheat CC between turbines.
 - Heat exchangers



Is it required?

At least to overcome losses in compressor and turbine

Minimum addition of fuel produces no useful work

Add more fuel to get useful work output

Is there is any limit of fuel-air ratio?

Working temperature of the highly stressed turbine blades

Working life required



Two possibilities

- At constant volume
- At constant pressure

Theory says

$\eta_{thermal}$ of: constant volume cycle > constant pressure

Practically

Constant volume combustion involves mechanical difficulties

Requires valves to isolate the CC from compressor and turbine

Combustion is intermittent – no smooth running of the machine

Discontinued

Constant pressure gas turbine

No valves and continuous



The two main factors affecting:

- Efficiencies of various components
- Turbine working temperature

Increase performance:

Higher these factors, higher the overall performance.

In fact, low efficiencies and poor turbine materials caused the failure of a number of early attempts.

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Gas Turbines - Cycle Arrangements

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Other components/arrangements

- Intercoolers between the compressors
- Reheat combustion chambers between the turbines
- Heat-exchanger which uses some of the energy in the turbine exhaust gas to preheat the air entering the CC

Advantages of these refinements

- Increase the power out and η of the plant
- At the expense of added complexity, weight and cost

How to link together?

- Affects the maximum overall $\eta_{thermal}$
- Variation of power output
 - One arrangement for varying load at constant speed
 - Another for driving a ship's propeller, Power \propto (Speed)³



Broad classification

1. Open cycle arrangement
2. Closed cycle arrangement

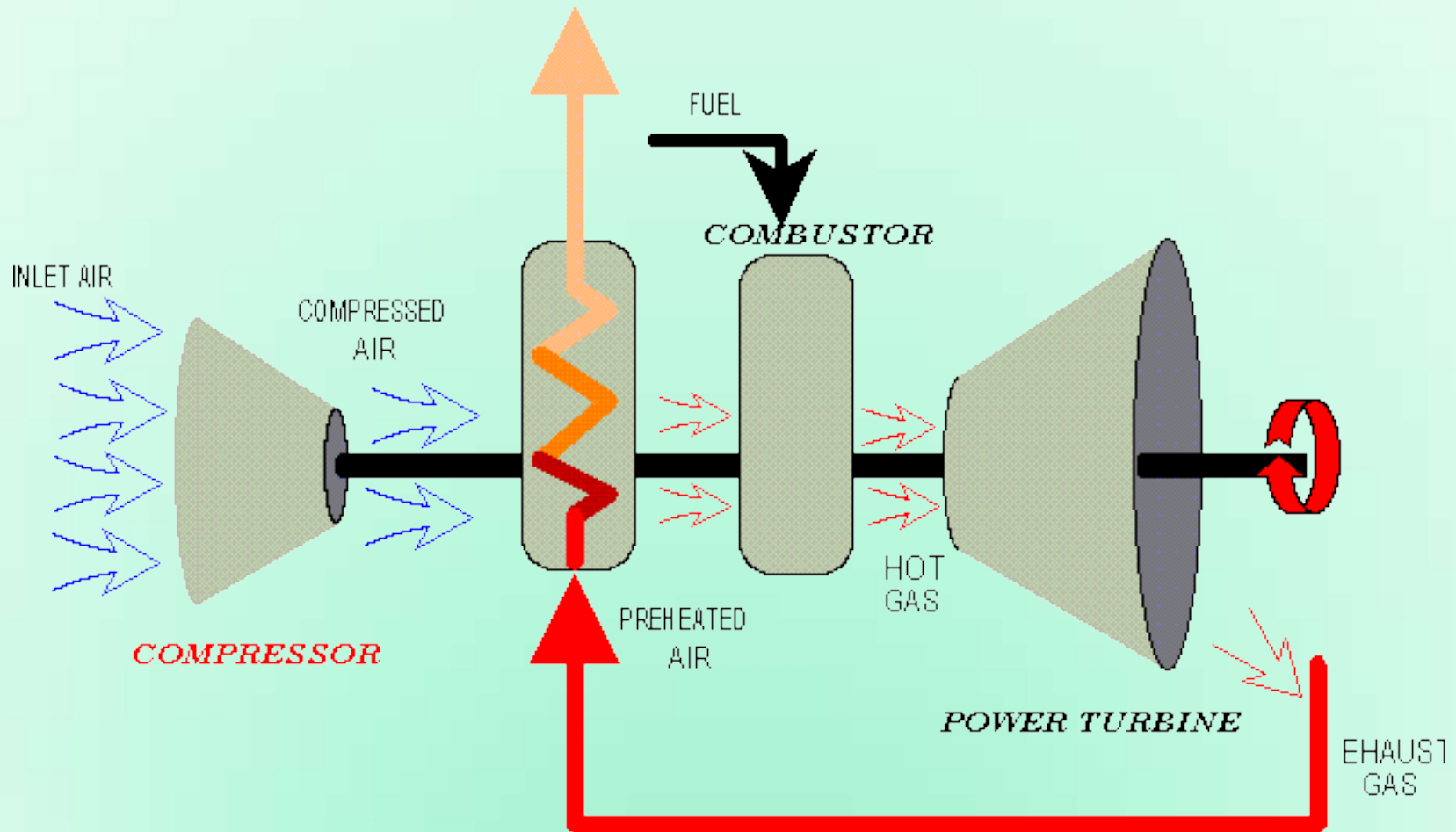
Open cycle arrangements

- Fresh atmospheric air is drawn into the circuit continuously
- Energy is added by the combustion of fuel in the working fluid
- Products of combustion expanded through turbine and exhausted into the atmosphere
- Most common

Closed cycle arrangements

- Usually, working fluid is not spoiled
- Heater or a gas boiler
- Similar to a steam turbine

Single Shaft Arrangement with Regeneration

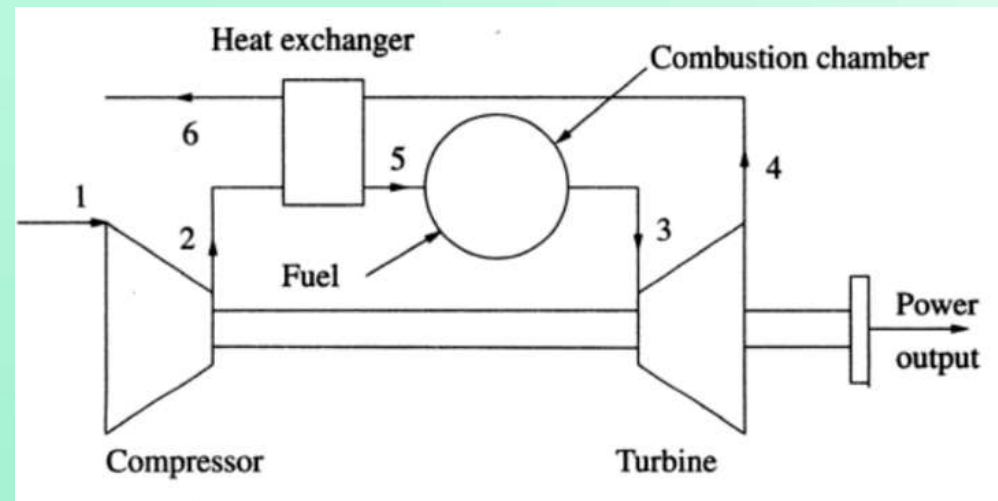


When?

- Fixed speed & load conditions (peak load power generation)
- Immediate response to change in load is not important
- η at part load is not important

Heat exchanger

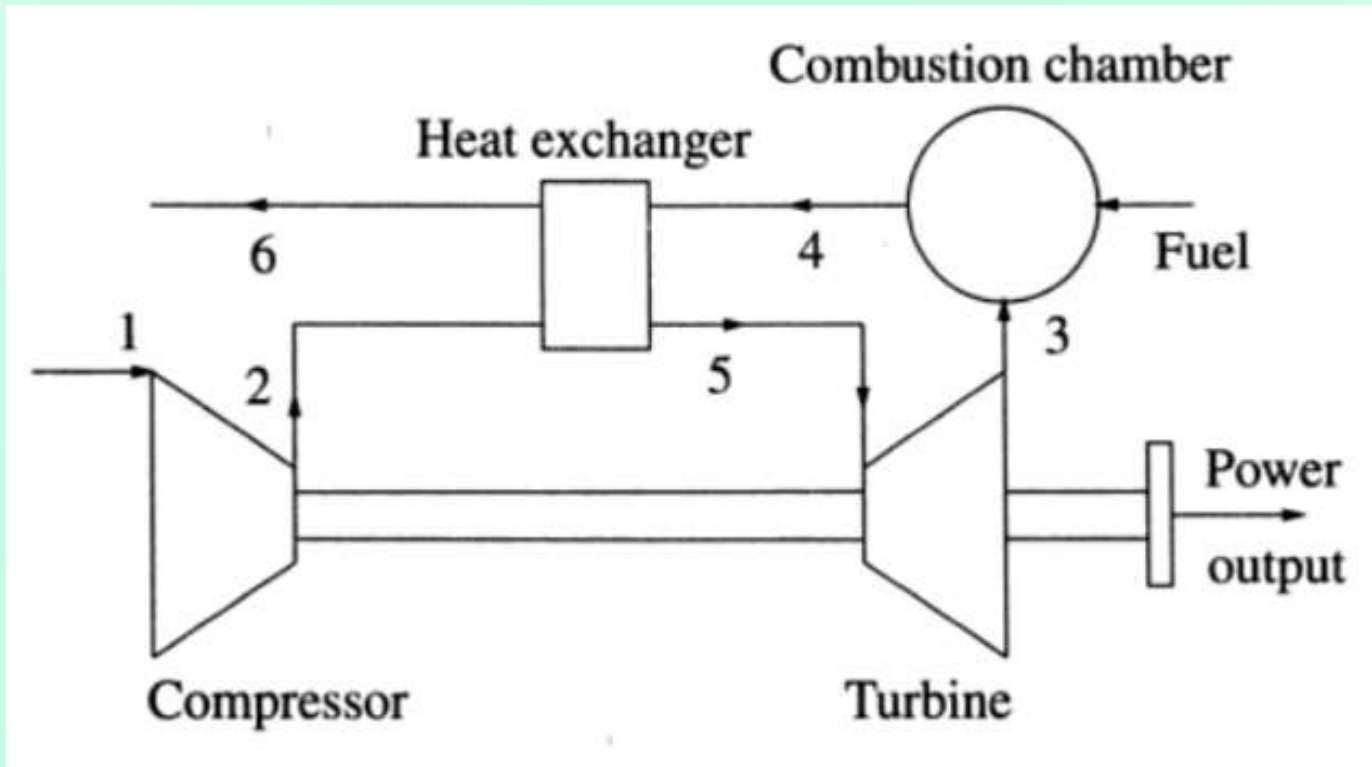
- Improves $\eta_{thermal}$ for a given size of the plant
- Power output reduces by 10% due to pressure losses in HE
- Reduces the fuel
- Advantage only at low r



When?

Possibility of corrode or erode the blades

Availability of dirty fuel (pulverized coal)



When?

Flexibility in operation

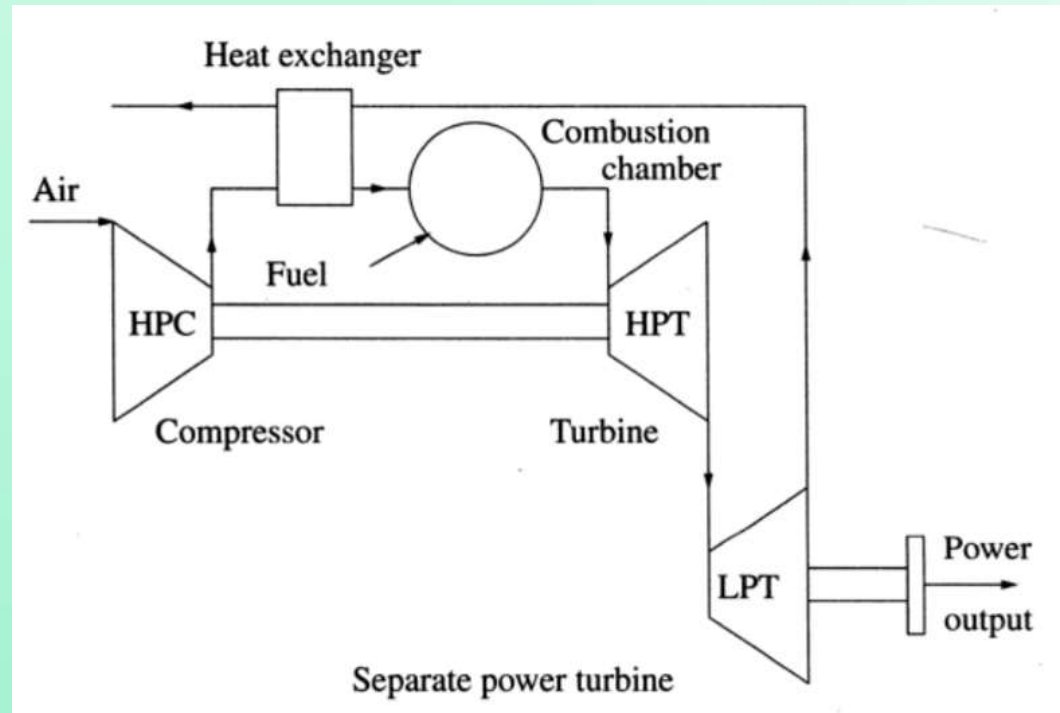
Pipeline compressor, marine propeller, road vehicle

Advantages

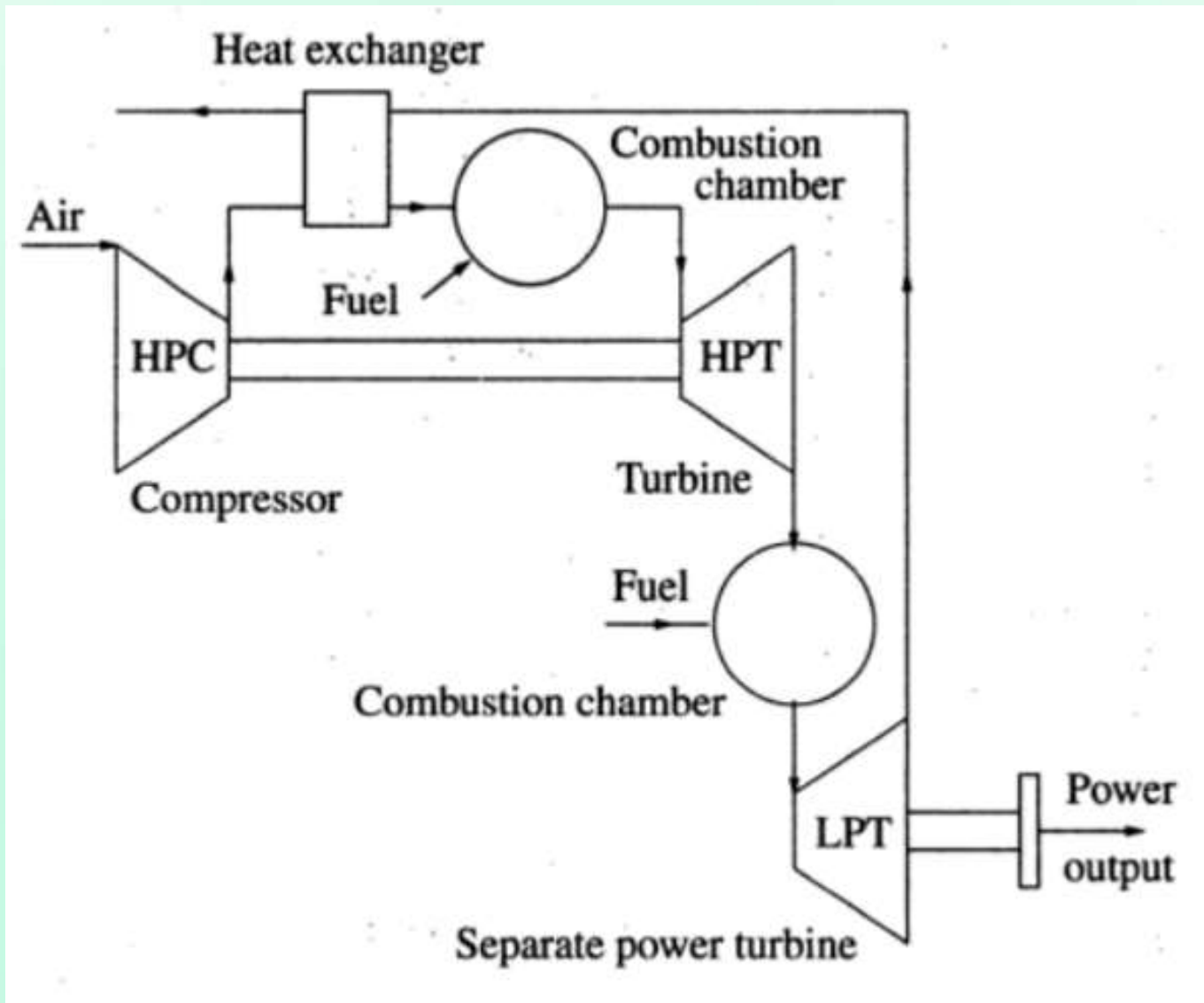
Easy start

Disadvantages

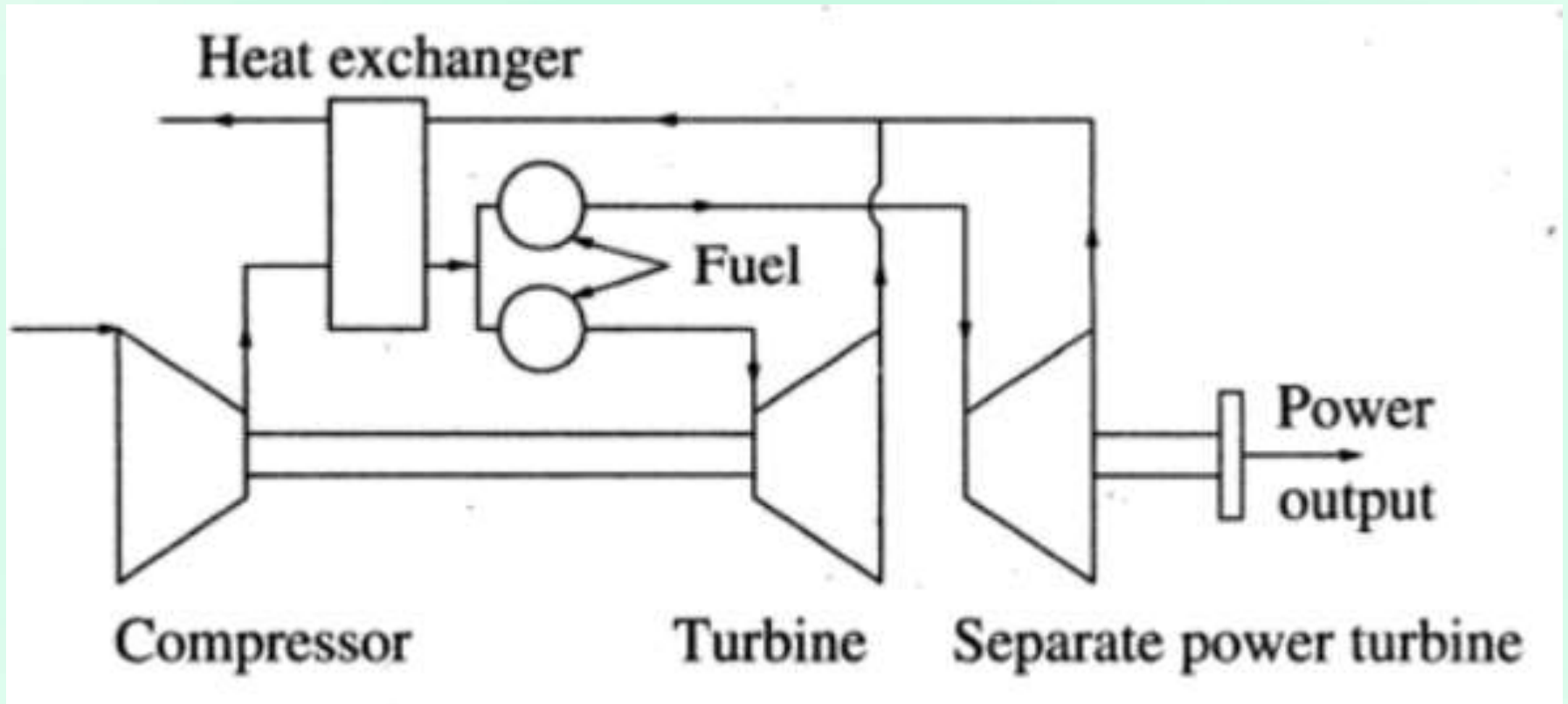
- Electrical shedding leads to overspeeding
- HPT, HPC at off loads?



Series Flow Twin Shaft Arrangement



Parallel Flow Twin Shaft Arrangement





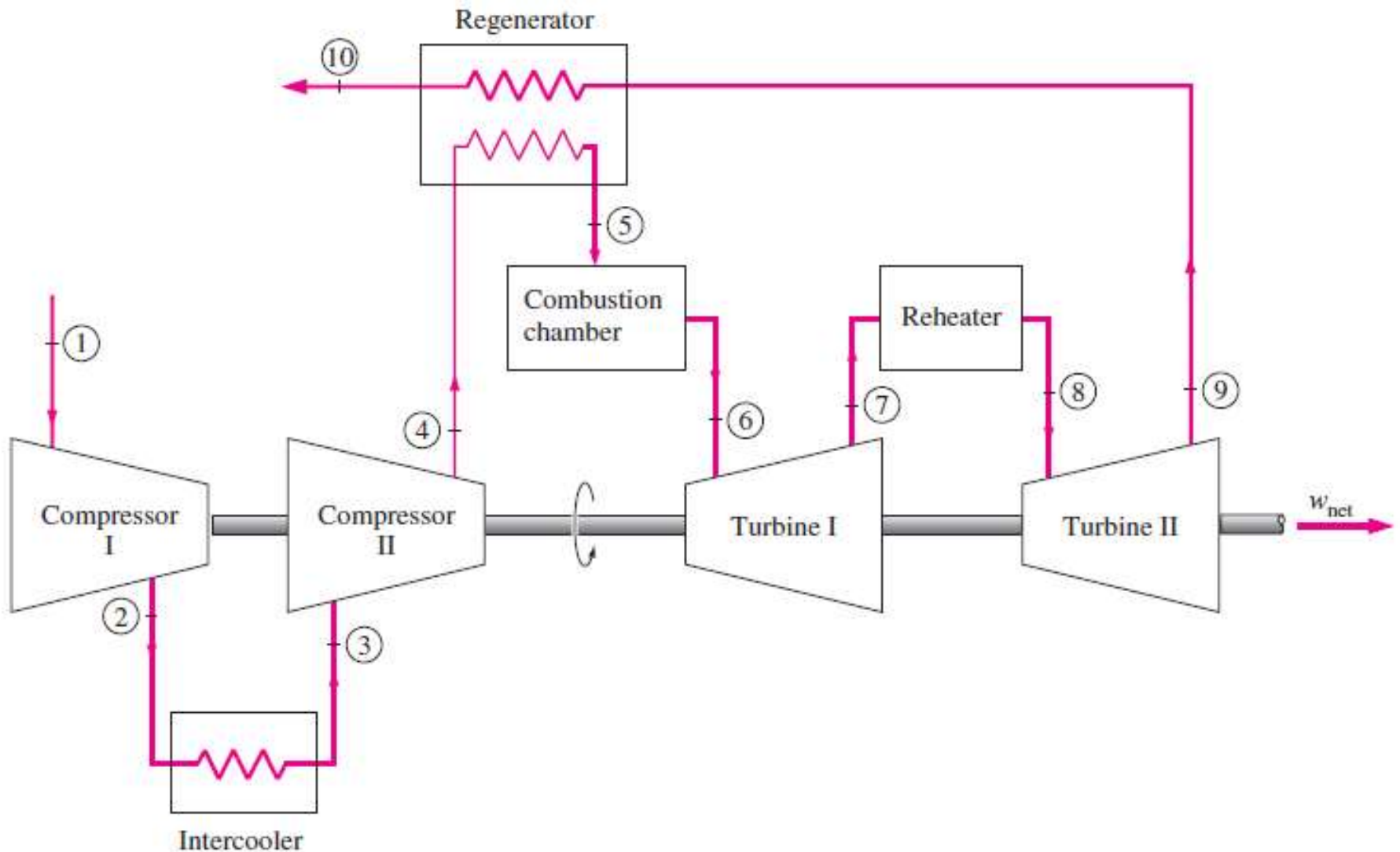
Performance can be improved

1. Reducing the work of compression
2. Increasing the work of expansion

How?

- For a given r , Power per unit quantity of working fluid $\propto T_{inlet}$
- Compression in stages with intercooling
- Expansion in stages with reheating the gas to the max. permissible temperature

Parallel Flow with Intercooling & Reheating





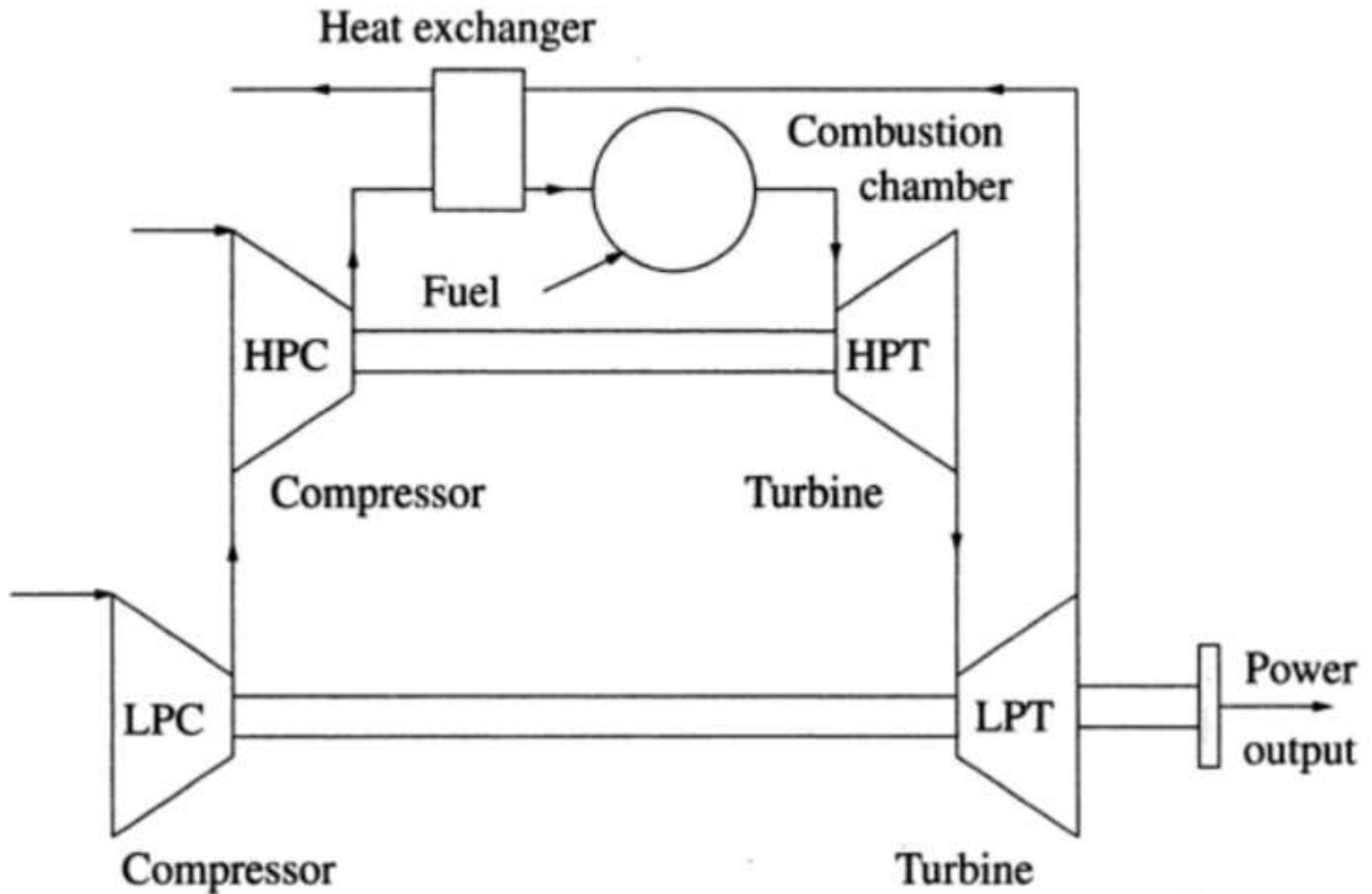
High pressure ratios are required

- $\eta_{axial} > \eta_{centrifugal}$ compressor
- Axial compressors - instability at off-design conditions
 - Vibrations – even at startup
 - Compressor exit is designed on the basis of flow and density
 - $\rho_{exit} \gg \rho_{inlet}$
 - At low speeds ρ_{exit} falls
- More dangerous at $r > 8$ in one compressor

How?

- Compressors at different rotational speeds
- Mechanically independent – needs individual turbines

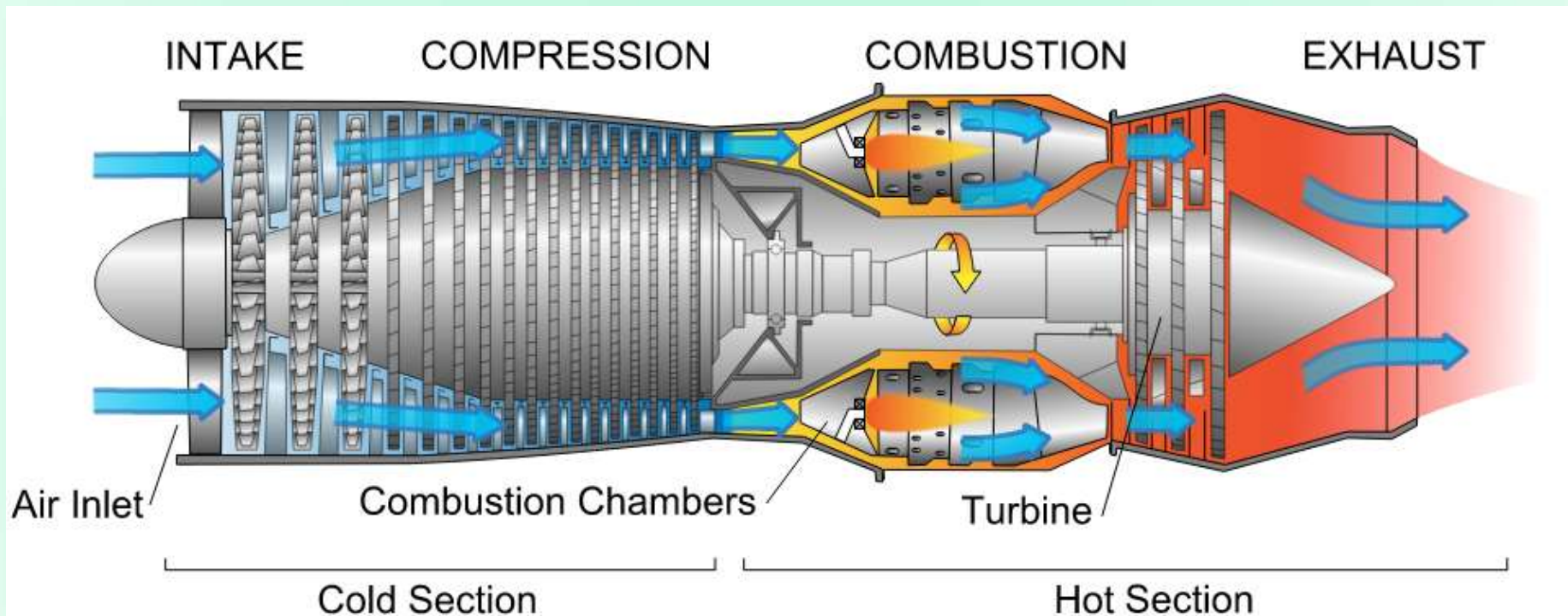
Twin Spool Arrangement



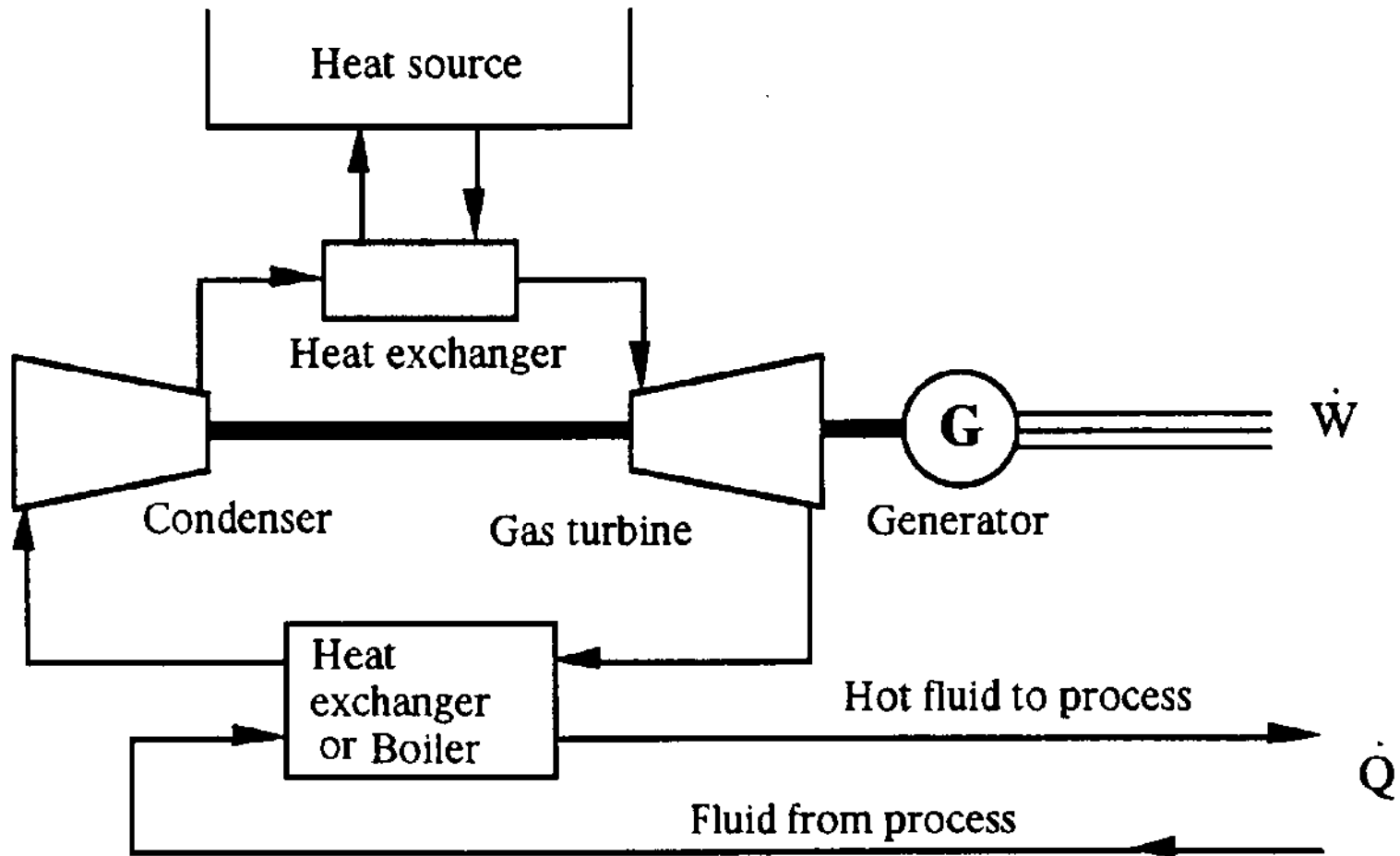
Multistage Compressor



High r or $\eta_{thermal}$ can also be safely achieved in a single compressor with several stages of variable stator blades



Closed Cycle Gas Turbine with Cogeneration System





Advantages

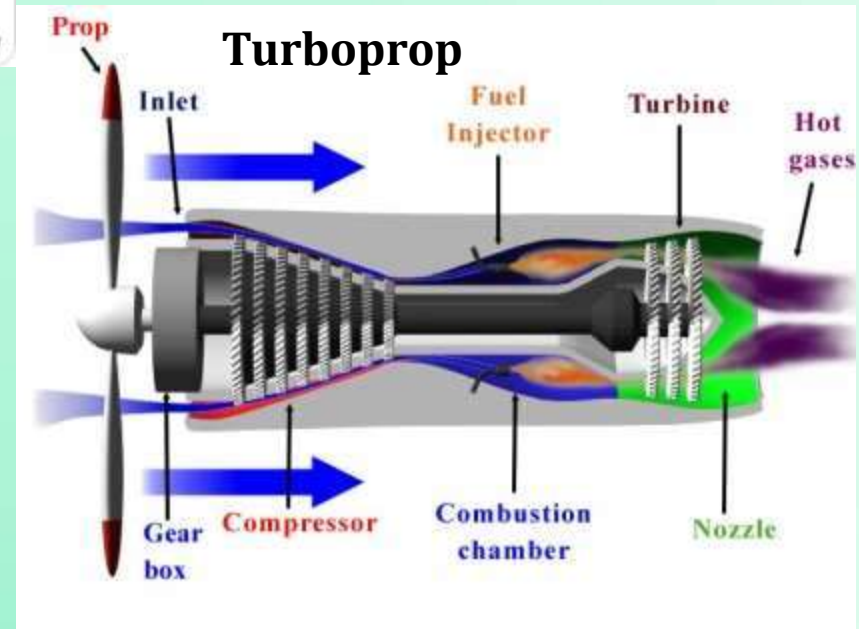
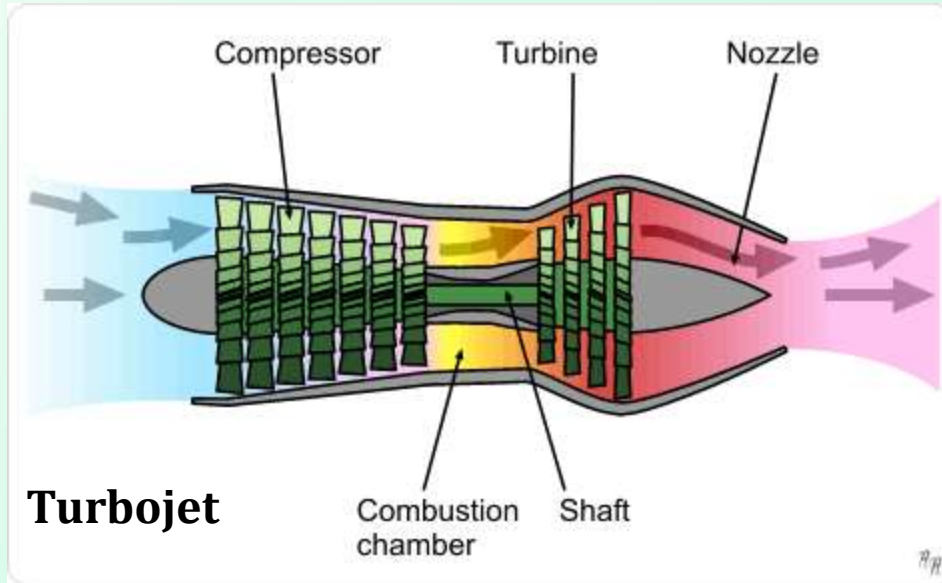
- No Erosion of turbine blades
- Continuous filtration of working fluid is not there
 - Once at startup
- Gases other than air can be used
- Cheaper fuels can be used
- Maintain r but increase pressure (there by increasing ρ)
- Reduces size of the plant for a given output
- Change the pressure level for dynamic control
 - However, maximum cycle temperature maintained
 - No change in overall efficiency

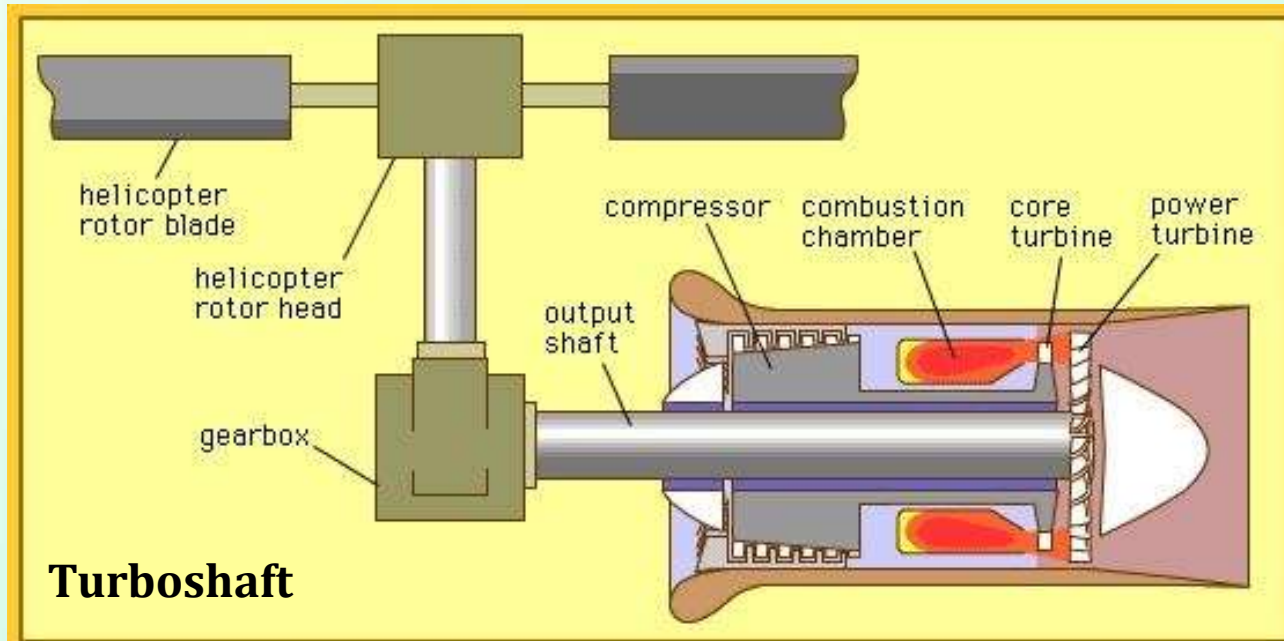


Disadvantages

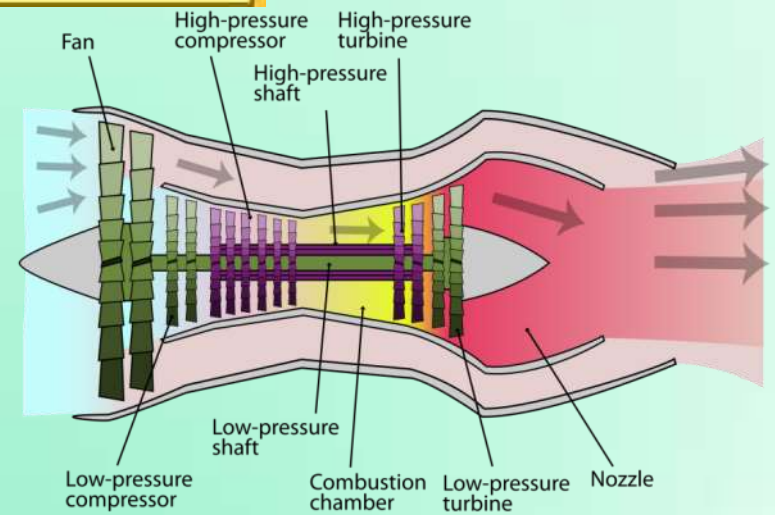
- We are again back to steam turbine mechanism
- Bulky heating system (gas boiler)
- Leak proof of the system
- Large capacity of cooler is necessary
- Only for stationary power plants

Aircraft Propulsion





Turboshaft



Turbofan (or bypass)



Compared with Aircraft gas turbine:

- The life of an industrial plant is of 11.5 years
- Size and weight is not of much importance
- The kinetic energy at turbine exhaust is wasted



Advantages over other Power plants

- Compact
- No cooling tower like that in a Steam Turbine
- Complete packages, built, tested and transported
 - Not often erected on site



Alstom

General Electric

Siemens-Westinghouse

Siemens, SGT-750, 39 MW



0.25 MW Steam turbine (right), AC generator (left)



Tube condenser is set beneath the turbine



Over Reciprocating engines

- High $\eta_{mechanical}$ due to less friction
- Better balancing
- Low cost than multi-cylinder petrol or diesel engines
- Power to weight to ratio

- External shape and size
- Cheaper fuels: benzene, powdered/pulverized coal
- Less lubrication
- Minimum maintenance
- Low operating pressures
- High operation speeds
- Silent, smokeless exhaust (abundant air)



Over Reciprocating engines

- Poor $\eta_{overall}$
 - Most of the energy goes in feeding compressor
- T_{max} limitation
- How to cool the blades?
- How to start the engine?
Complicated



Jet exhaust was noisy but ignored for military applications

- Noise \propto (Jet velocity)⁸
- Turbofan - Maintain thrust with low velocity but at higher airflow

Gas turbines for non-aircraft applications offer relatively clean-burning power plant

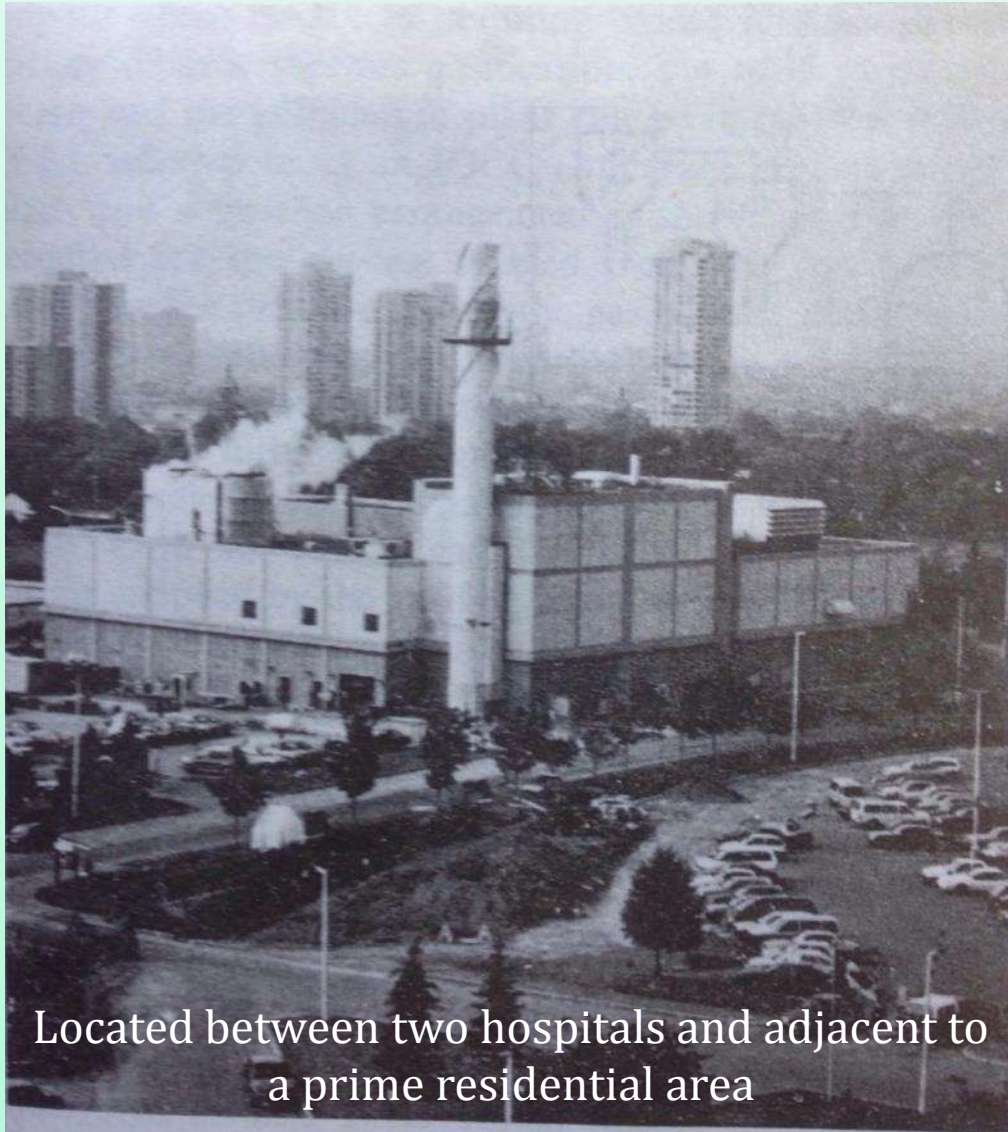
Main combustion product of any hydrocarbon fuel is CO₂

- Global warming – Greenhouse effect

Improve engine efficiencies to burn less fuel

Alternative fuels

70 MW Combined Cycle Plant



Located between two hospitals and adjacent to a prime residential area

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Gas Turbines – Shaft Power Ideal Cycles

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- There are several possibilities in gas turbine cycle arrangements
- Shall we study all of them?
Large number of performance curves

Two categories

1. Shaft Power Cycle: Marine and land based power plants
2. Aircraft Propulsion Cycle
Performance depends significantly upon speed and altitude

Let us start with:

Performance of ideal gas turbine cycles

Ideal?

Perfection of the individual components is assumed

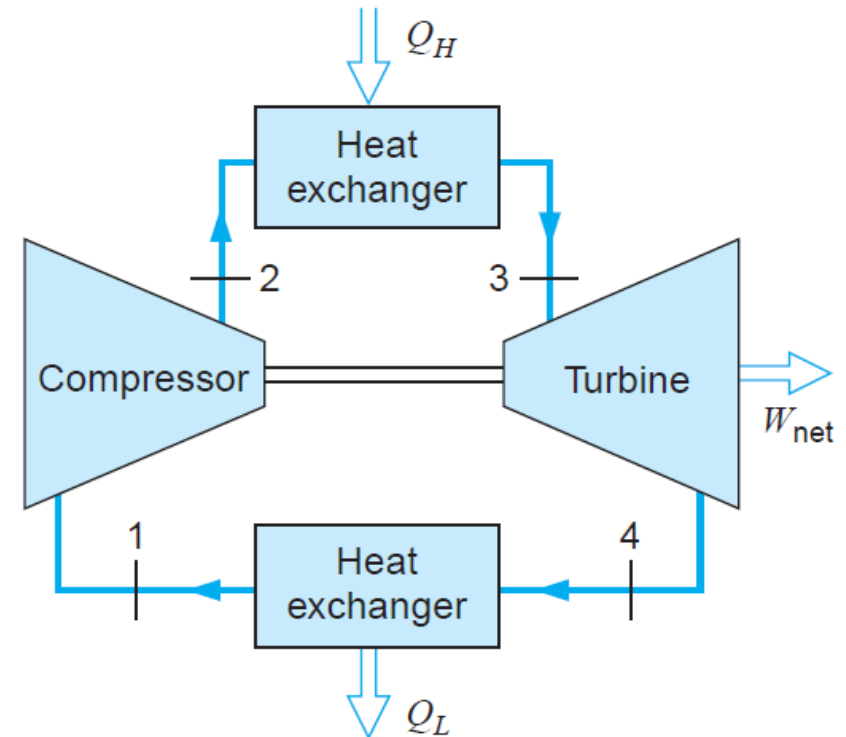
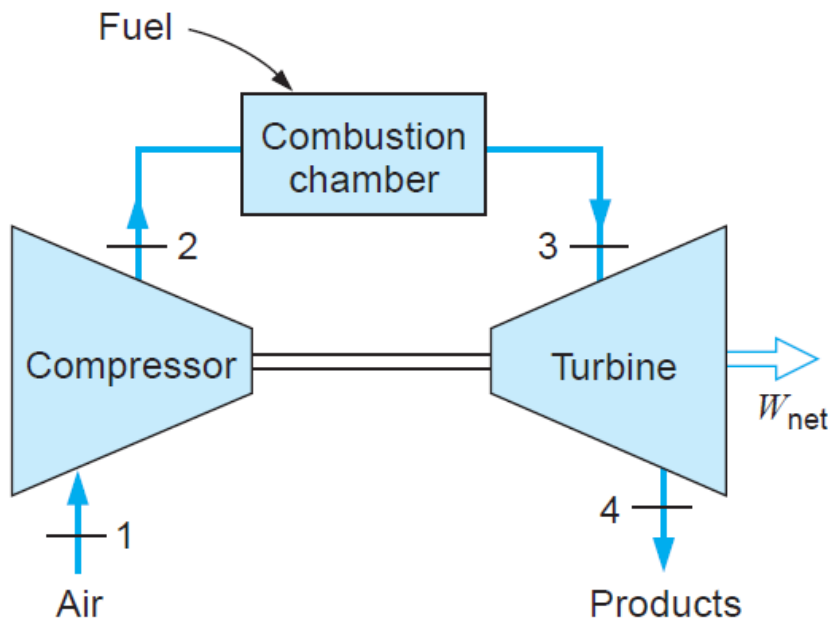
Specific work output and cycle efficiency = $f(r, T_{max})$



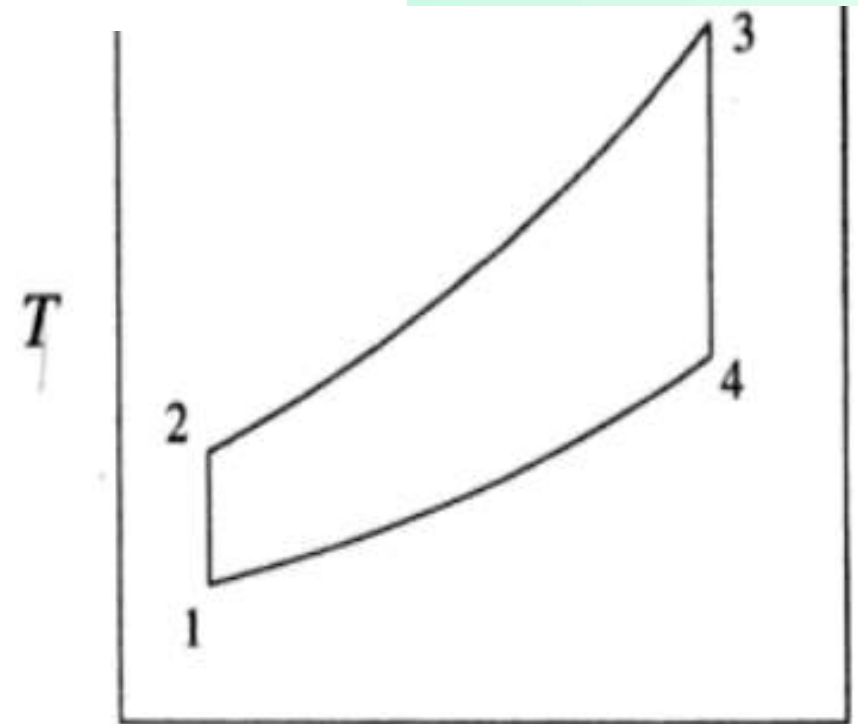
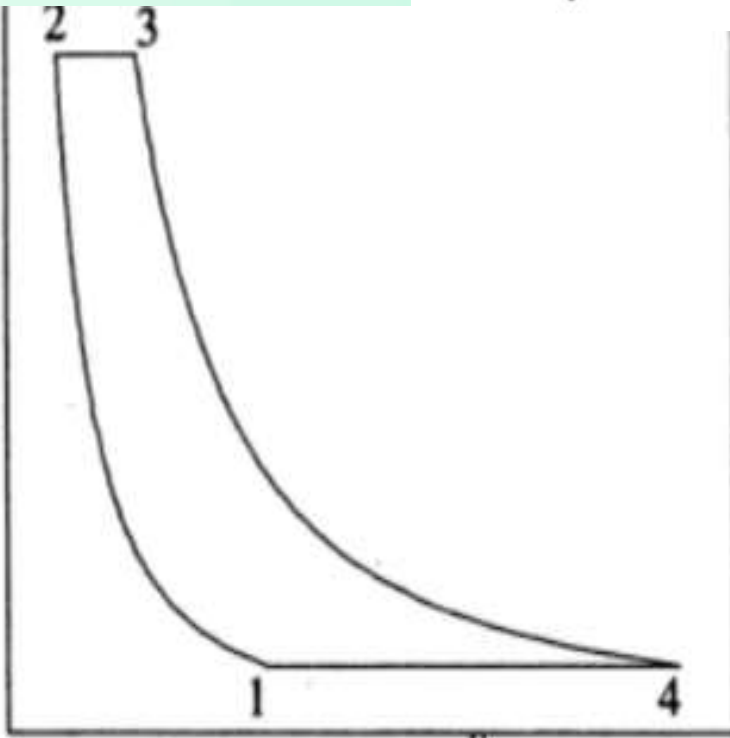
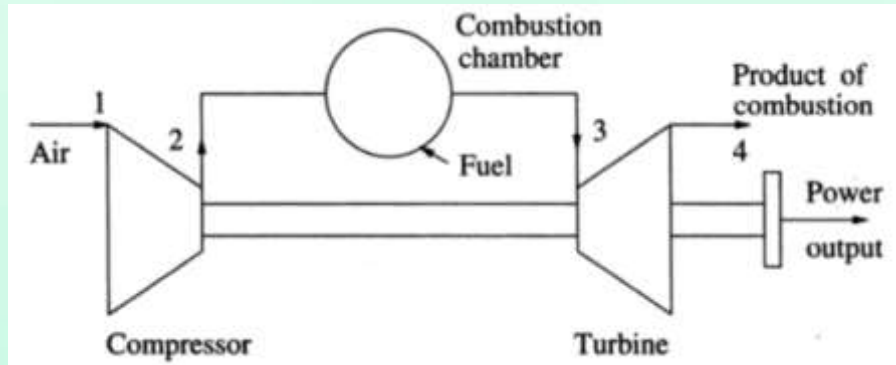
The air-standard Brayton cycle

- Compression and expansion processes are reversible and adiabatic, i.e., isentropic
- Negligible change in kinetic energy of the working fluid between inlet and outlet of each component
- No pressure loss
- Working fluid has the same composition throughout the cycle
 - What does it mean?
 - Ideal cycle: open or closed (doesn't make any difference)
- Working fluid is a perfect gas with constant specific heats
- Mass flow rate is constant
- Heat transfer in a heat-exchanger is complete
 - Temperature rise on cold side = temperature drop on hot side

Gas Turbine: Open or Closed Cycle



Brayton (Joule) Cycle





$$Q = (h_2 - h_1) + \frac{1}{2}(c_2^2 - c_1^2) + W$$

$$W_{12} = -(h_2 - h_1) = -c_p(T_2 - T_1)$$

$$\eta = \frac{\text{net work output}}{\text{heat supplied}} = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_2)}$$

$$\frac{T_2}{T_1} = r^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4} \text{ where } r = \frac{p_2}{p_1} = \frac{p_3}{p_4}$$

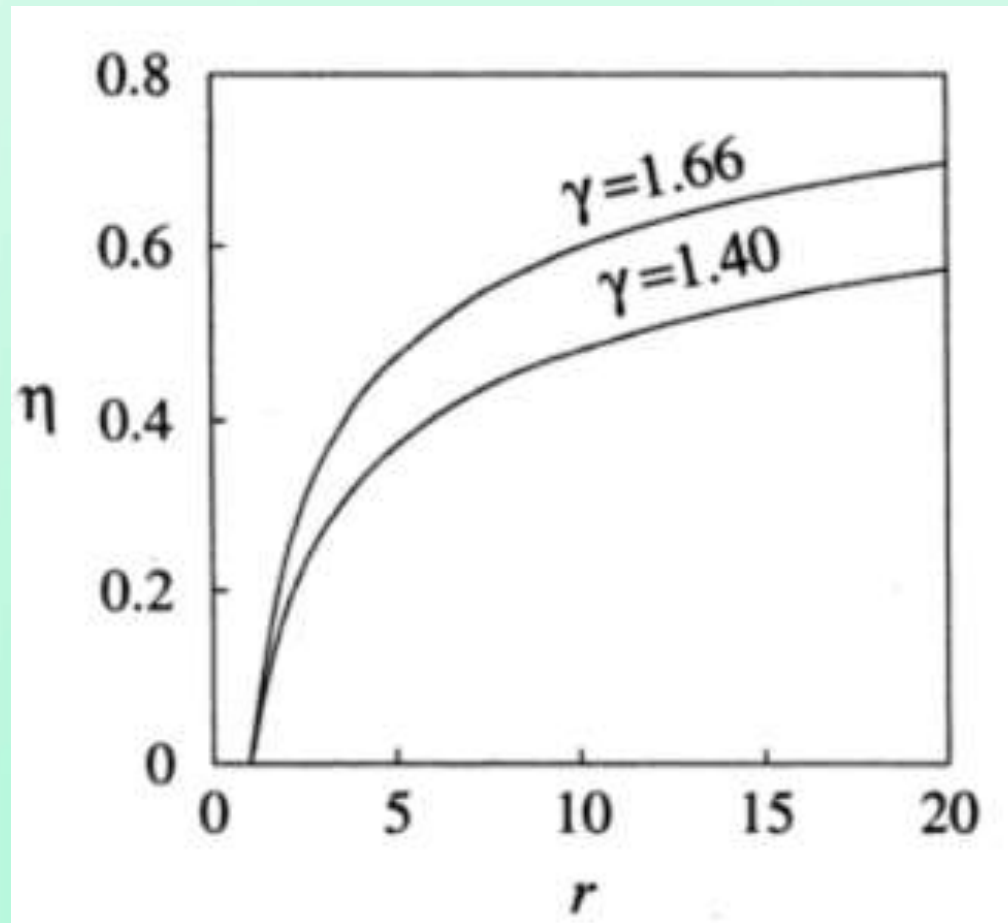
$$\eta = 1 - \frac{1}{r^{\frac{\gamma-1}{\gamma}}}$$

Simple Gas Turbine Cycle : Efficiency



Air ($\gamma = 1.4$), Argon ($\gamma = 1.66$)

However, this theoretical advantage may not be realized in reality



$$\eta = 1 - \frac{1}{c}$$
$$c = r^{\frac{\gamma-1}{\gamma}}$$



$$\frac{W}{c_p T_1} = t \left(1 - \frac{1}{c} \right) - (c - 1)$$

$$\text{where } t = \frac{T_3}{T_1}$$

$$c = r^{\frac{\gamma-1}{\gamma}}$$

Maximum specific work output at $c = \sqrt{t}$ obtained by $\frac{d}{dc}$
 $t = c^2$

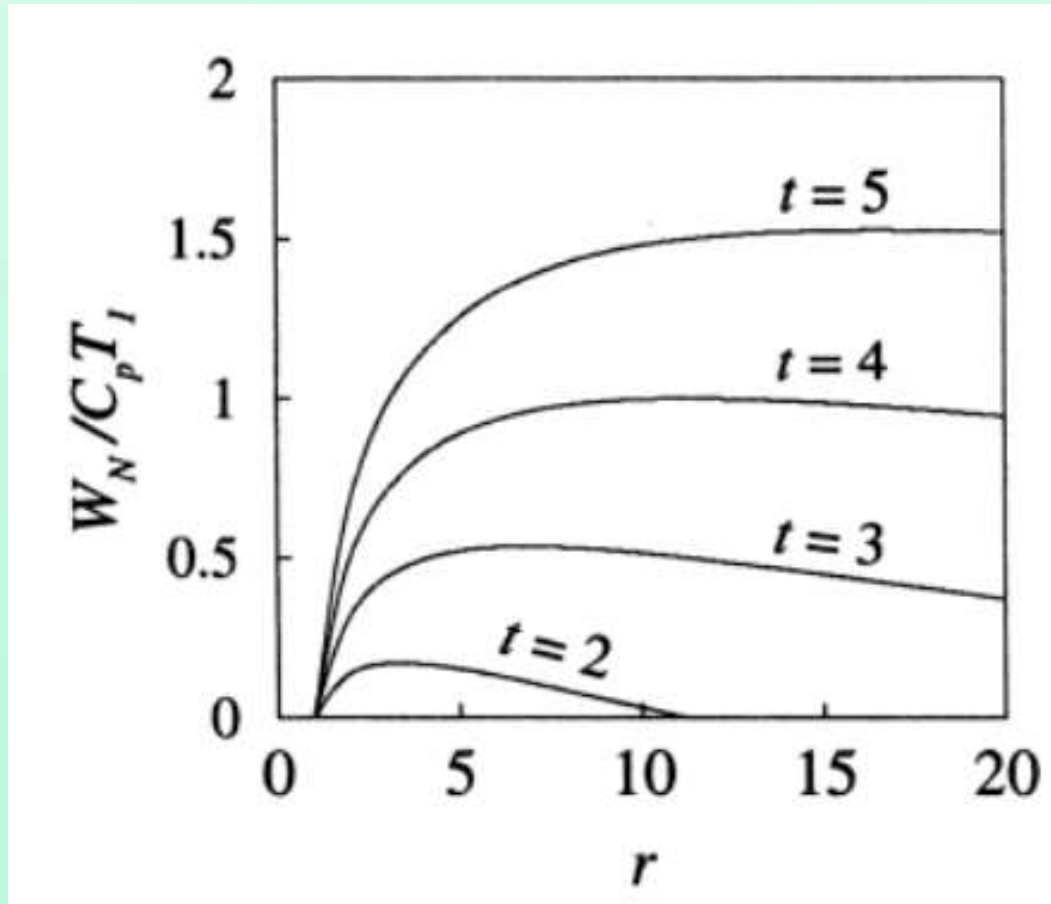
$$\Rightarrow \frac{T_3}{T_1} = \frac{T_2}{T_1} \frac{T_3}{T_4}$$

Specific work output is maximum at $T_2 = T_4$

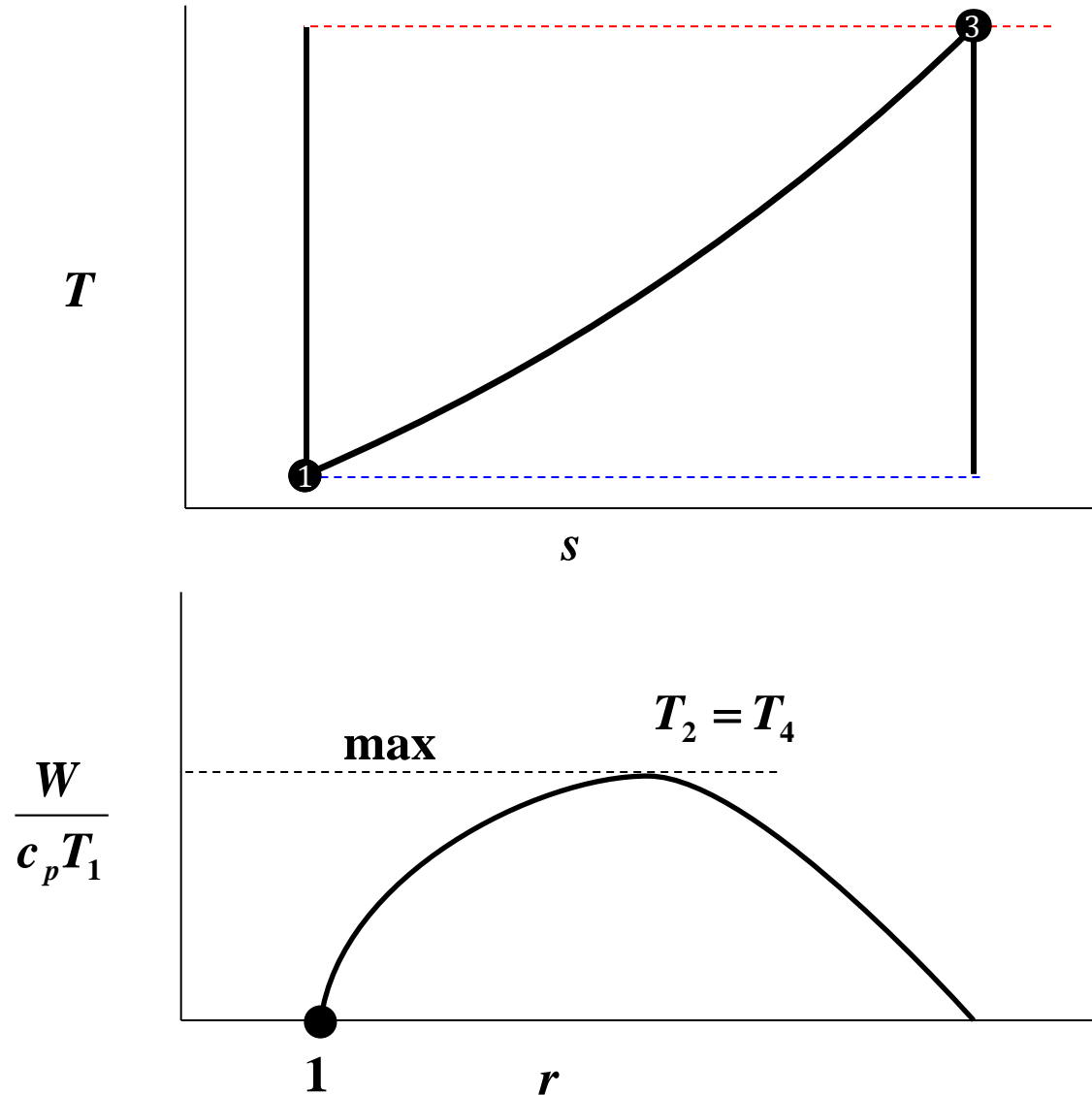
Simple Gas Turbine Cycle : Specific Work Output



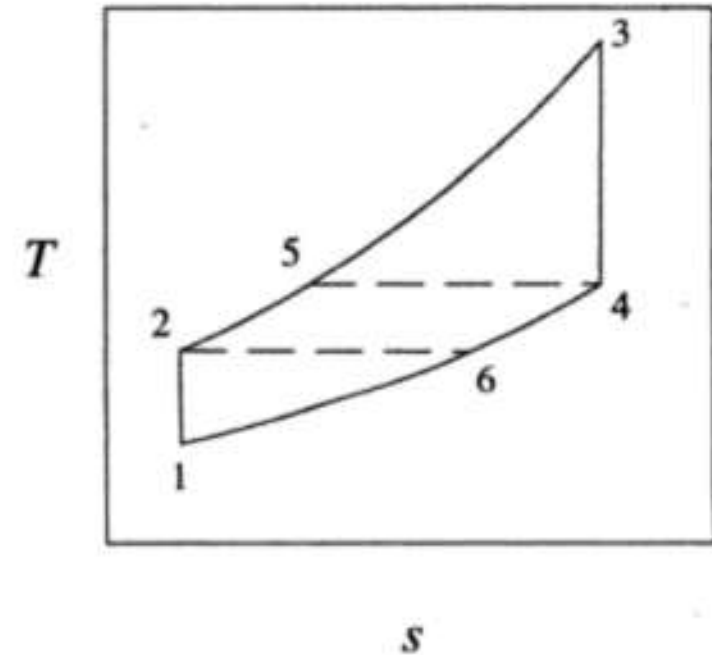
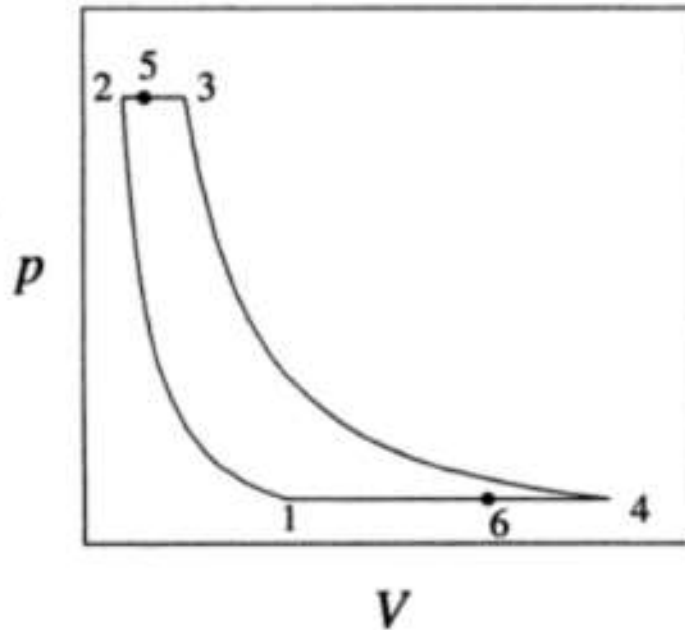
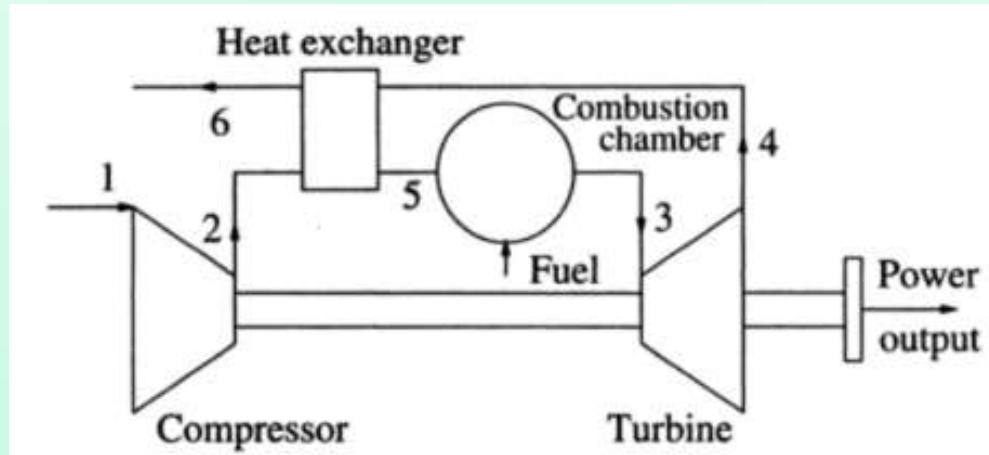
$$\frac{W}{c_p T_1} = t \left(1 - \frac{1}{c} \right) - (c - 1)$$



Simple Gas Turbine Cycle : Specific Work Output



Heat Exchanger Cycle





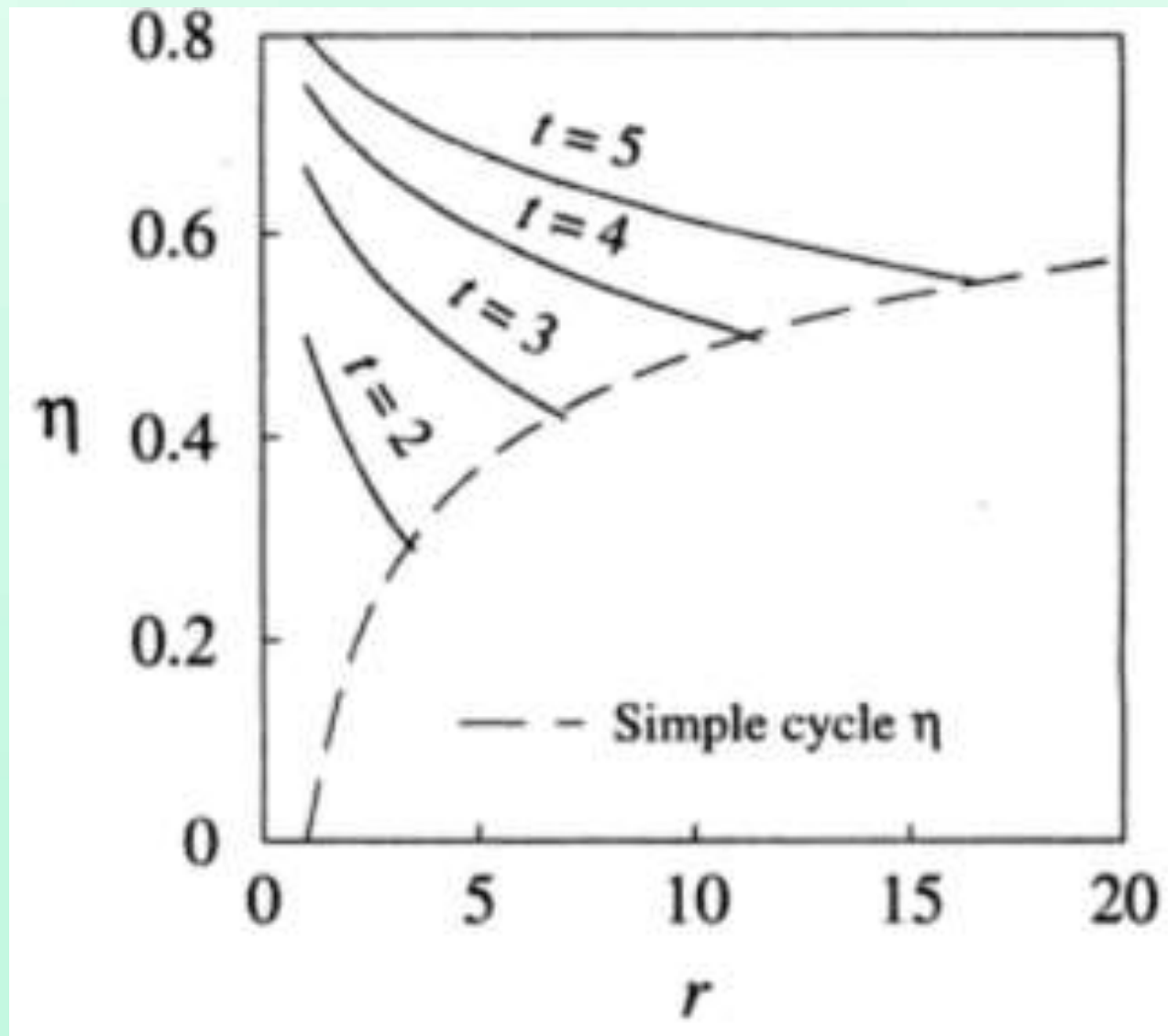
$$\eta = 1 - \frac{c}{t}$$

- η reduces as r increases (opposite to simple cycle)
- With higher ratios, η are higher without regeneration
- η increases rapidly with T_{max}
- Lower r and higher T_{max} are favorable

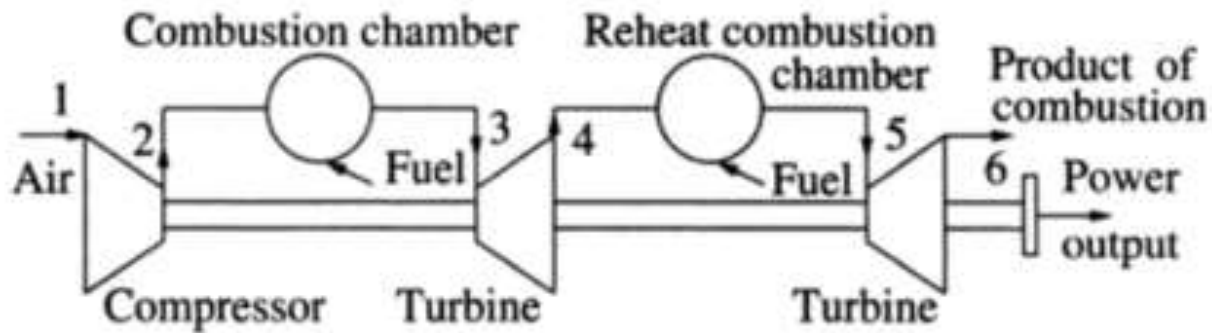
$$\frac{W}{c_p T_1} = t \left(1 - \frac{1}{c} \right) - (c - 1)$$

- The specific work output is unchanged with a heat-exchanger

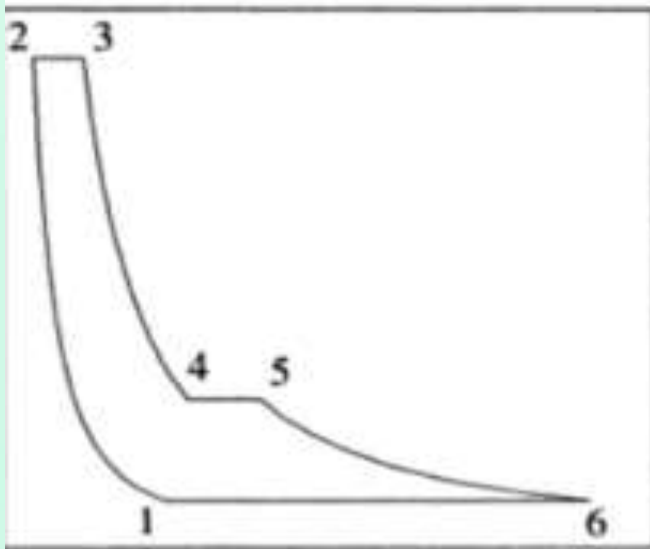
Heat Exchanger Cycle: Efficiency



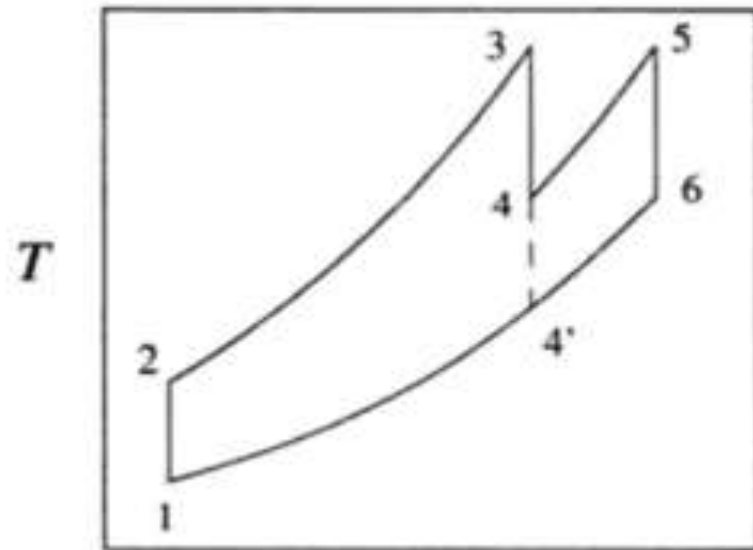
Reheat Cycle



$$(T_3 - T_4) + (T_5 - T_6) > (T_3 - T'_4)$$



V



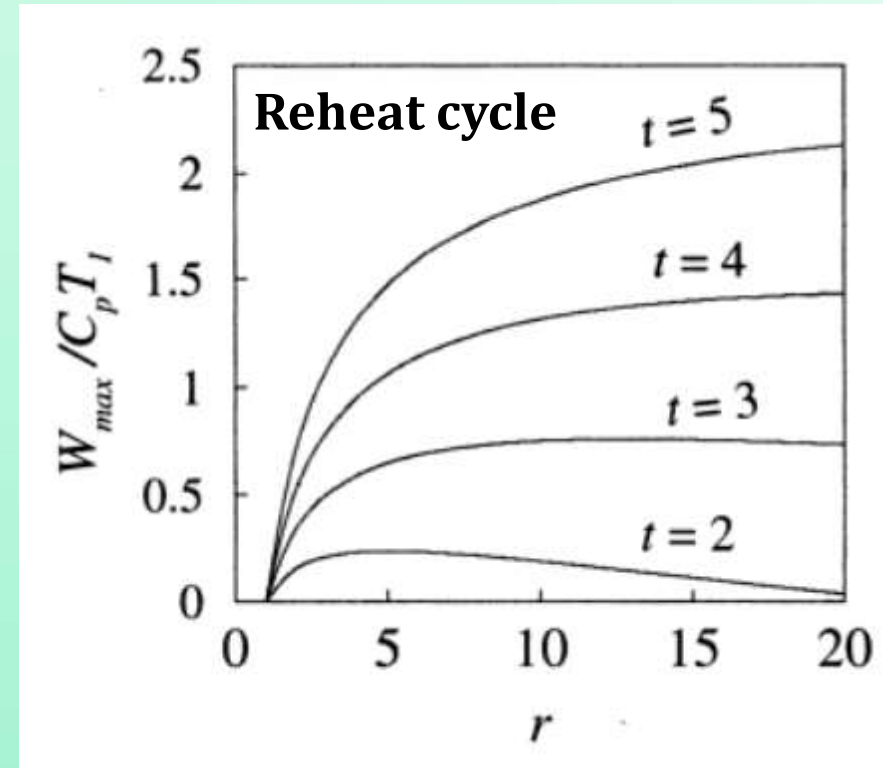
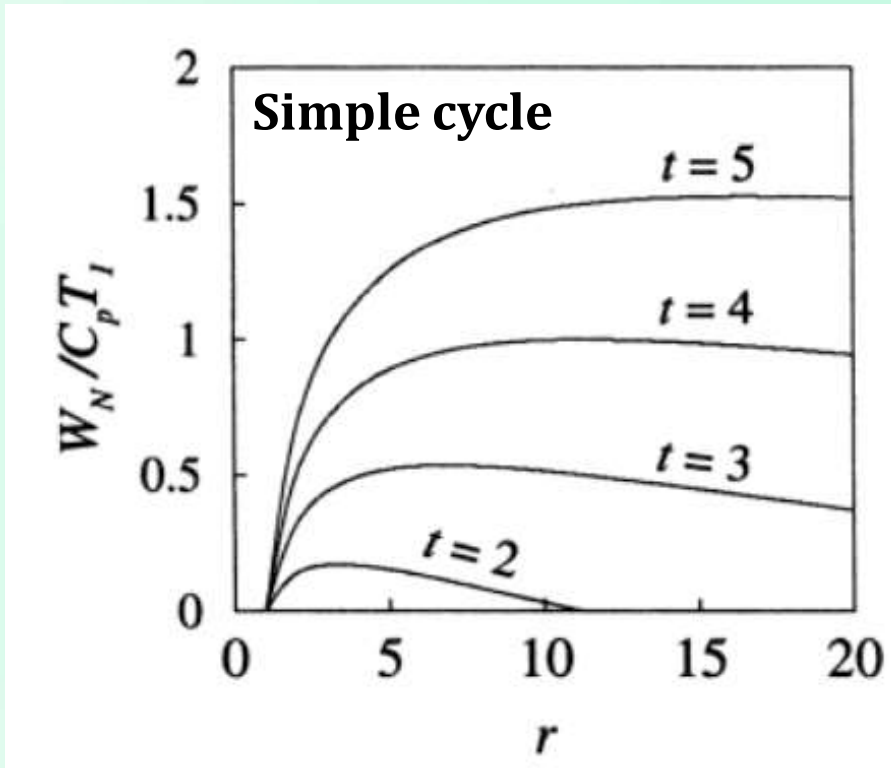
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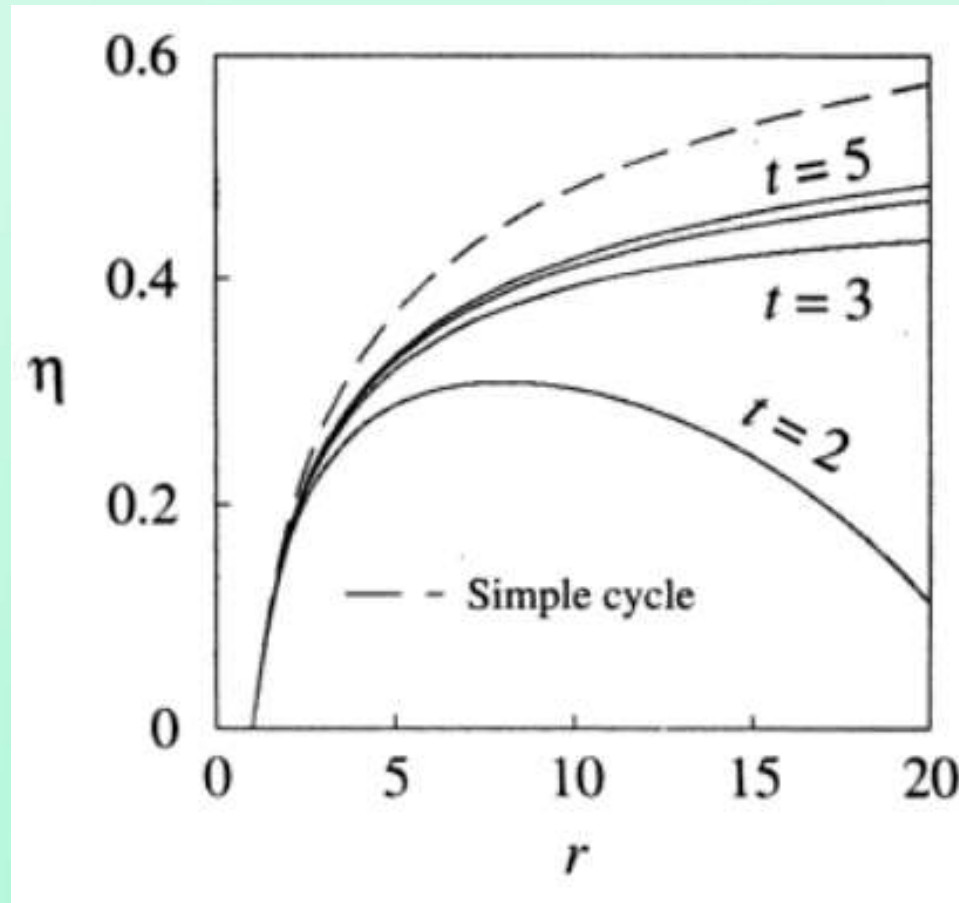
Reheat Cycle: Specific Work Output



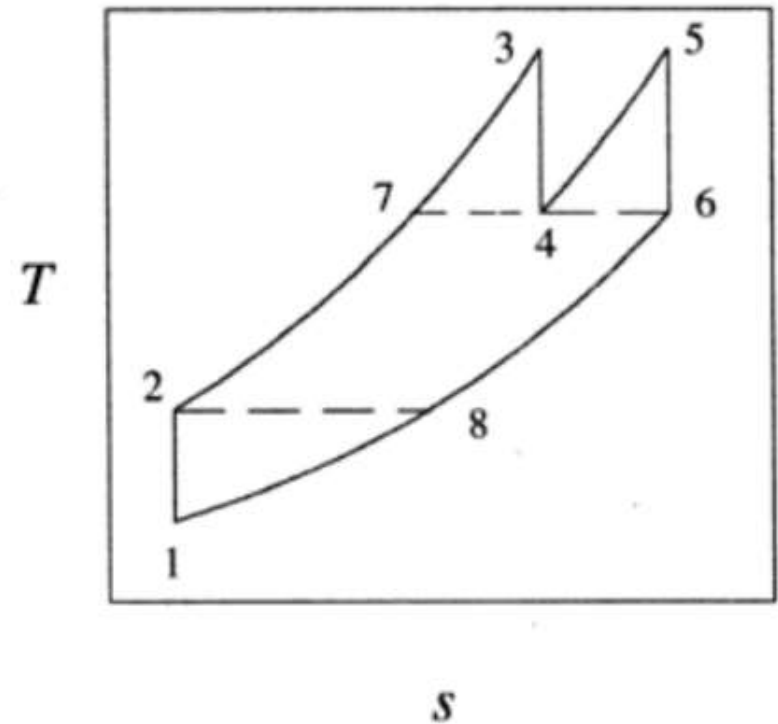
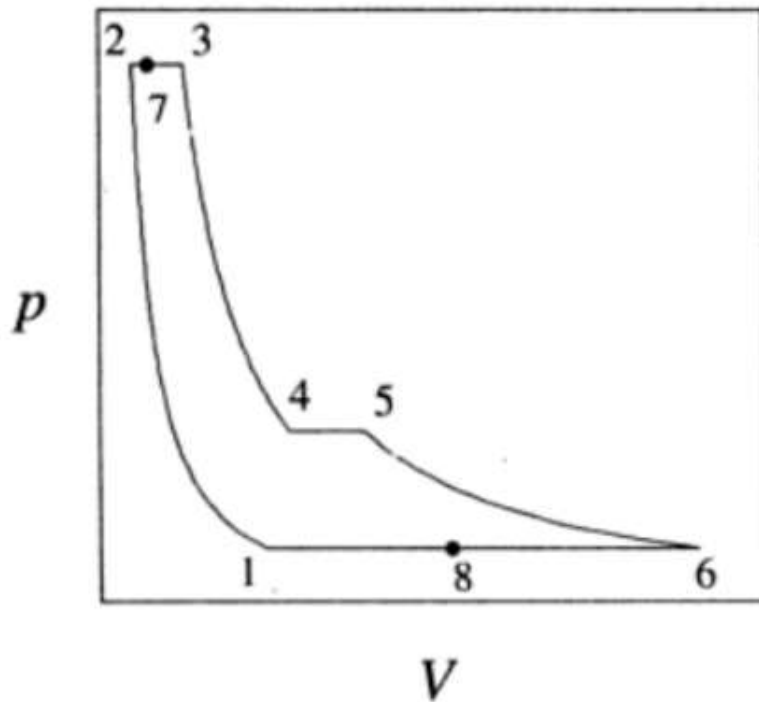
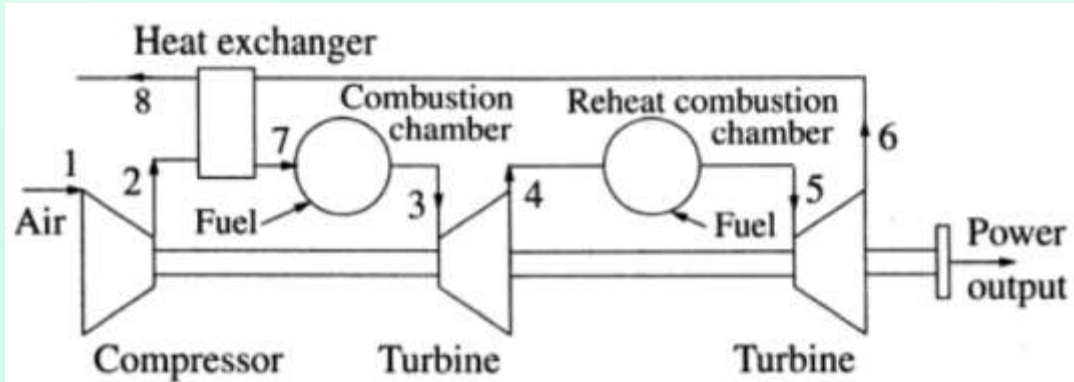
$$\frac{W_{\max}}{c_p T_1} = 2t - c + 1 - \frac{2t}{\sqrt{c}}$$



$$\eta_{\max} = \frac{2t - c + 1 - 2t/\sqrt{c}}{2t - c - t/\sqrt{c}}$$



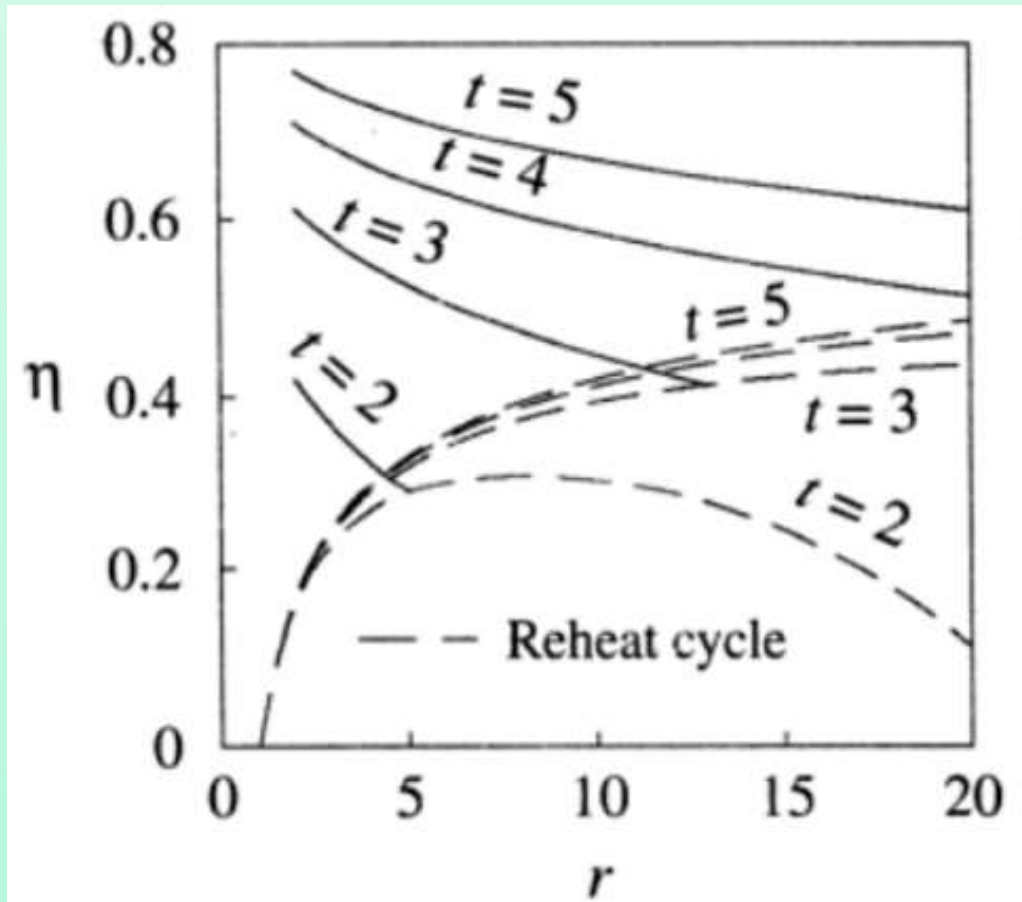
Reheat & Heat Exchange Cycle



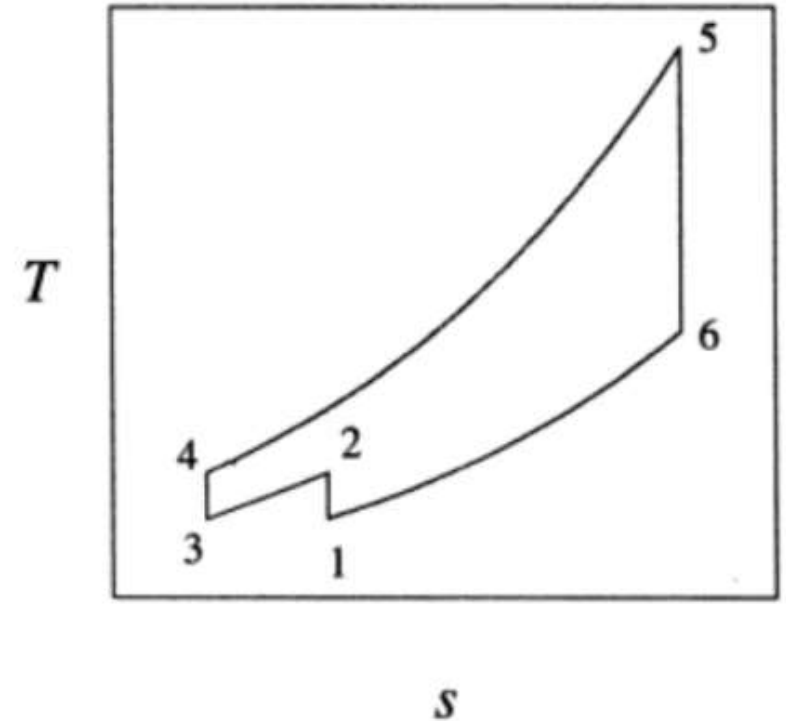
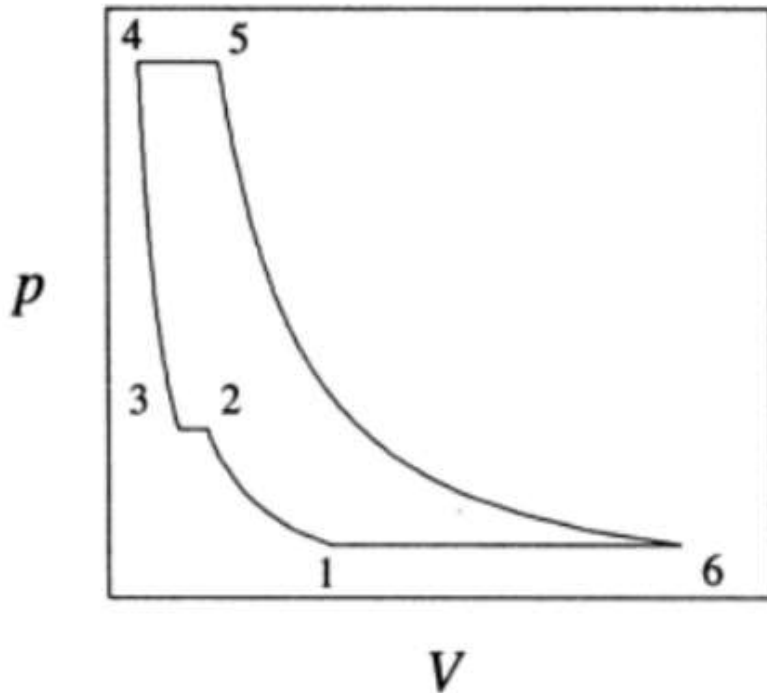
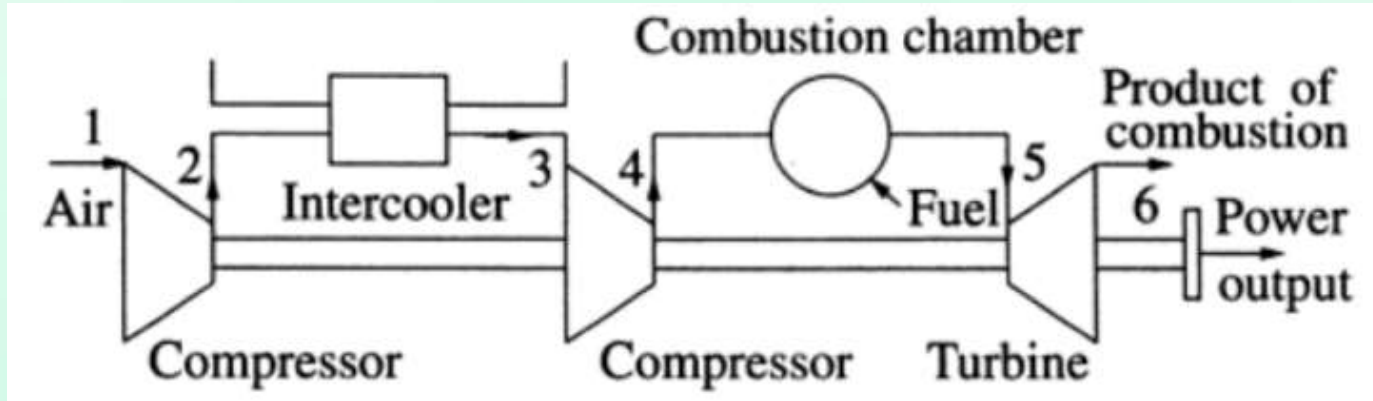
Reheat & Heat Exchange Cycle: Efficiency



$$\eta_{\max} = 1 - \frac{c - 1}{2t - 2t/\sqrt{c}}$$



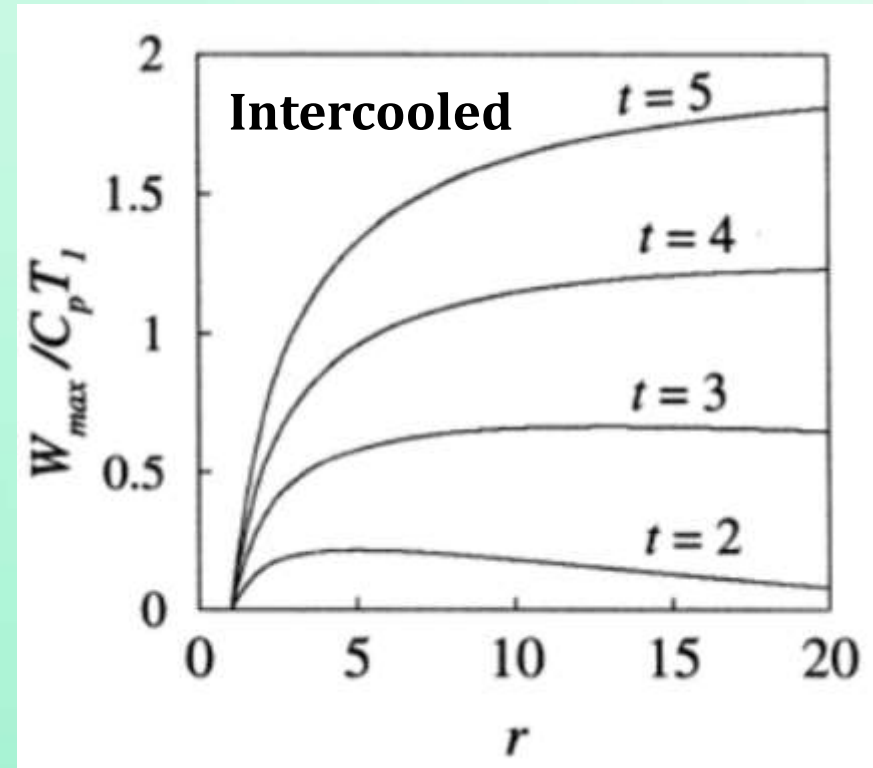
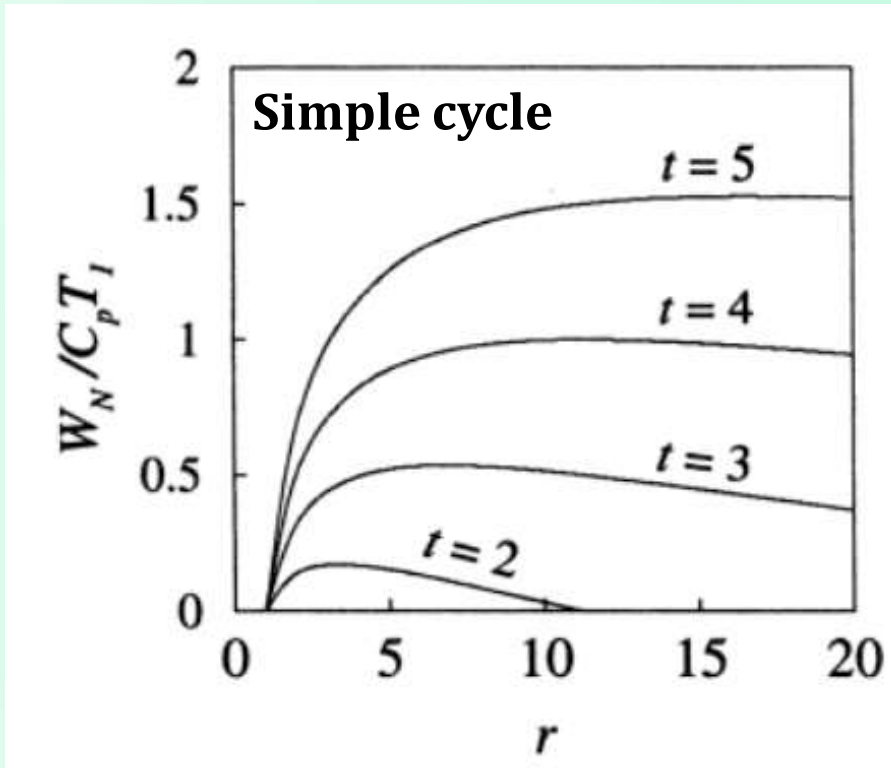
Intercooled Cycle



Intercooled Cycle: Specific Work Output



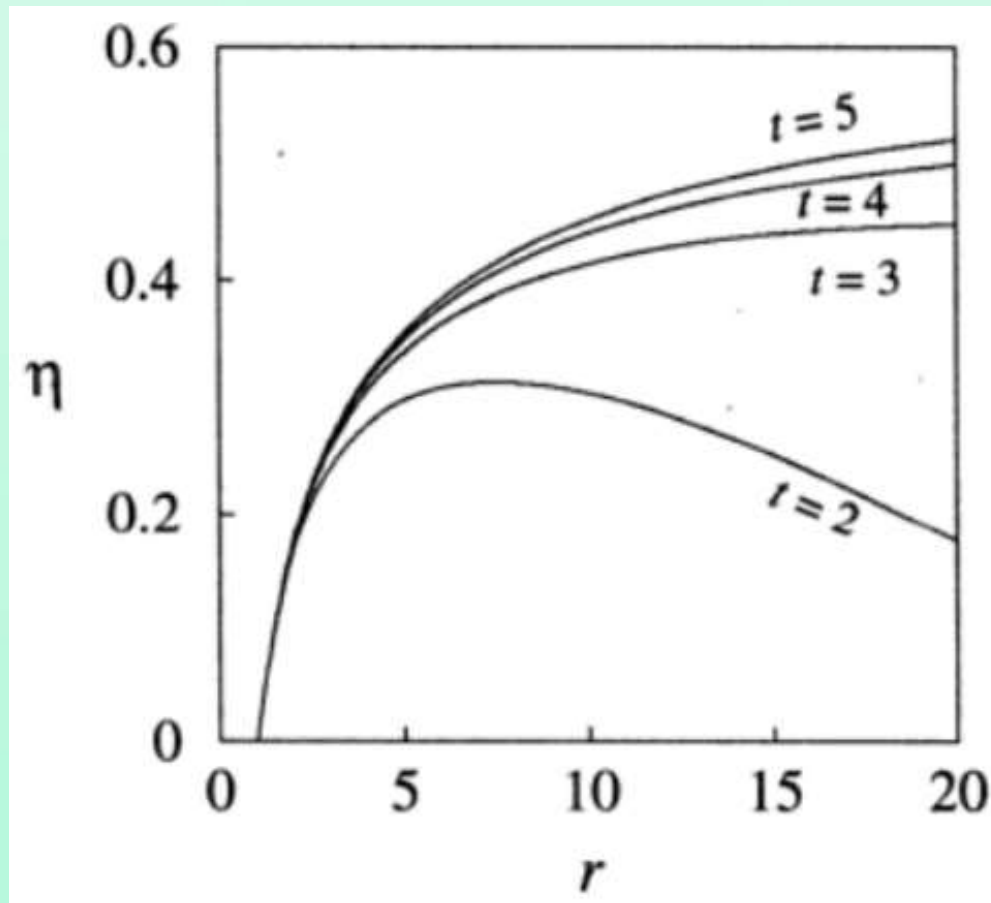
$$\frac{W_{\max}}{c_p T_1} = t - \frac{t}{c} - 2\sqrt{c} + 2$$



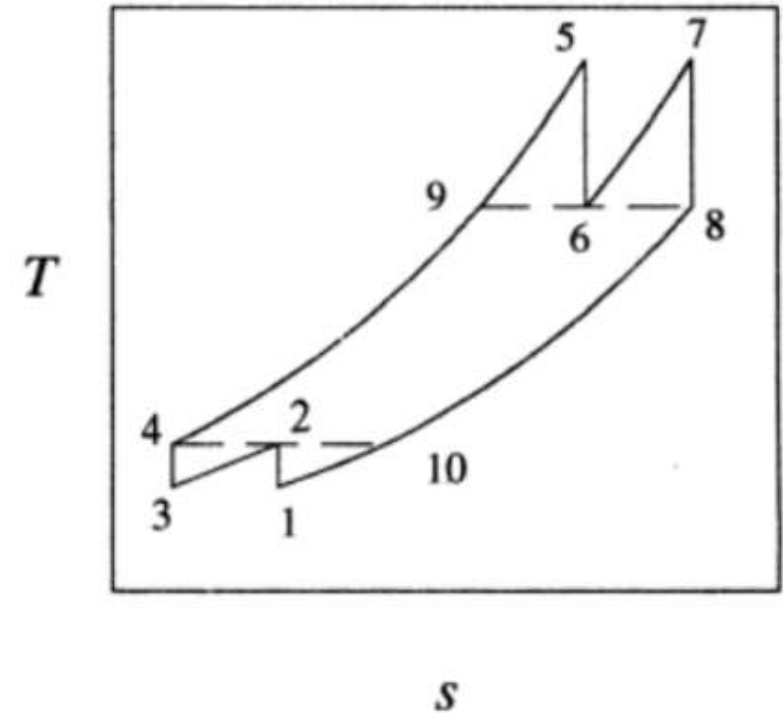
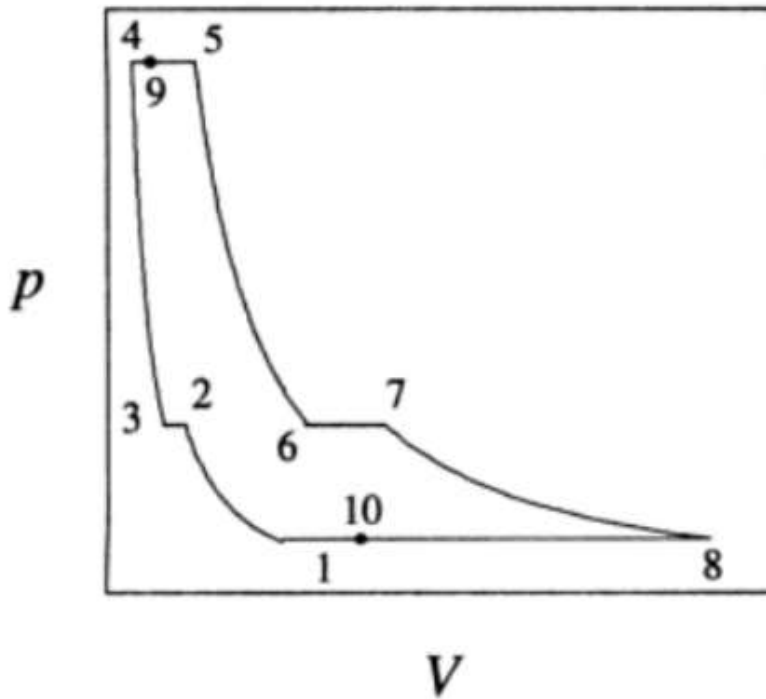
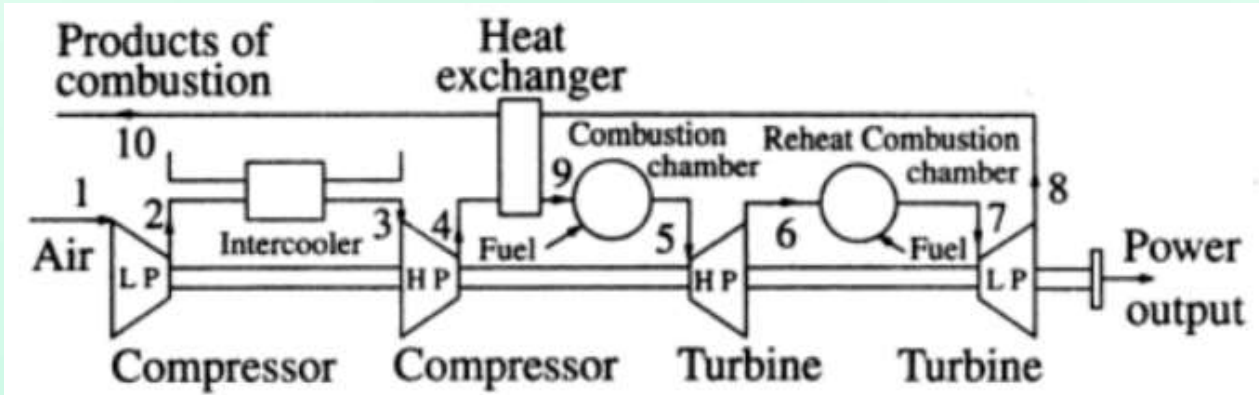
Intercooled Cycle: Efficiency



$$\eta_{\max} = 1 - \frac{t/c + \sqrt{c} - 2}{t - \sqrt{c}}$$



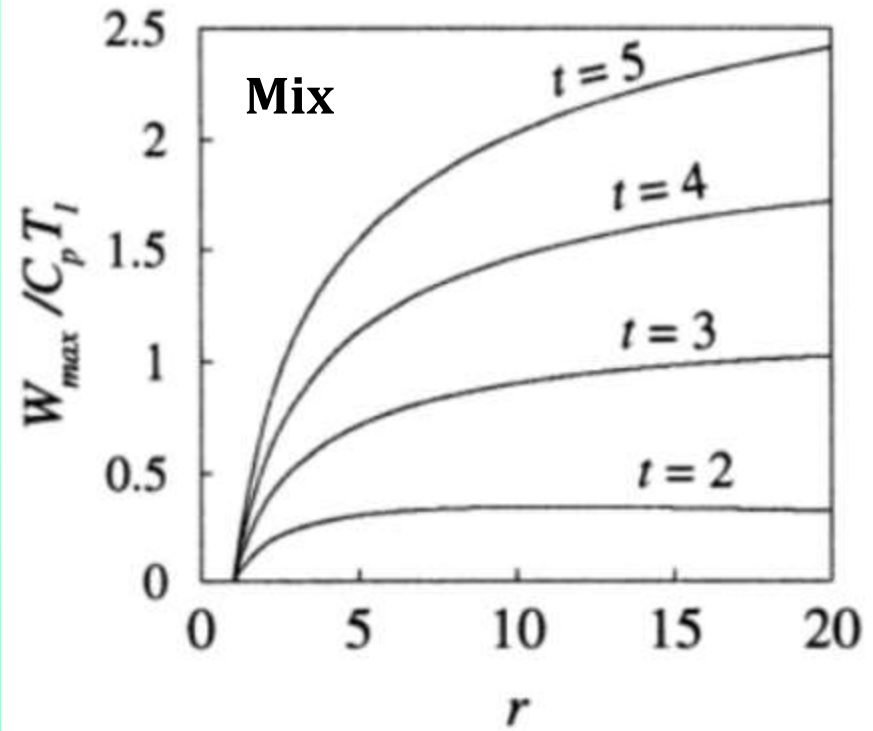
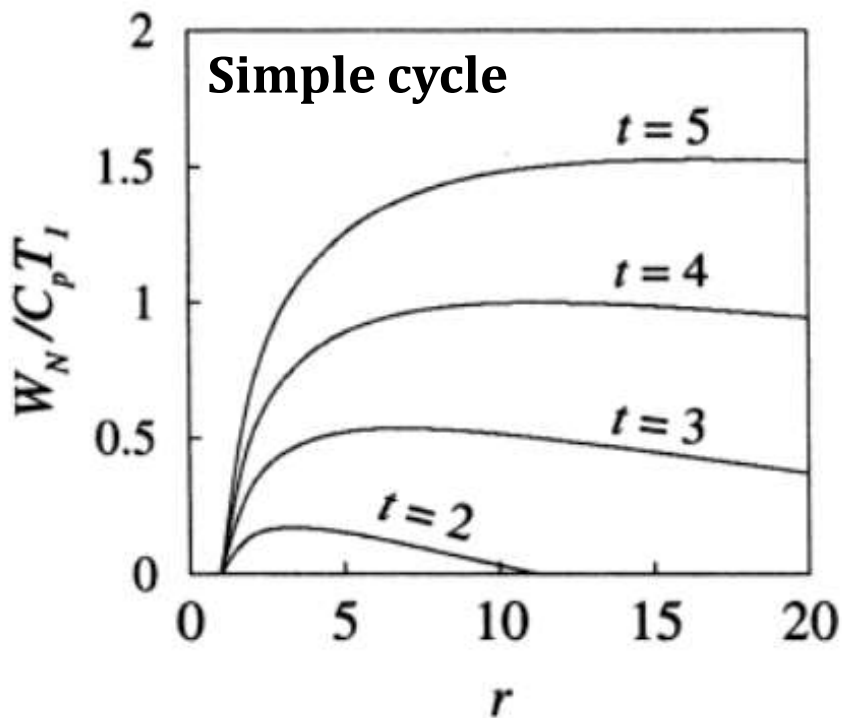
Intercooled, Reheat & Heat Exchange



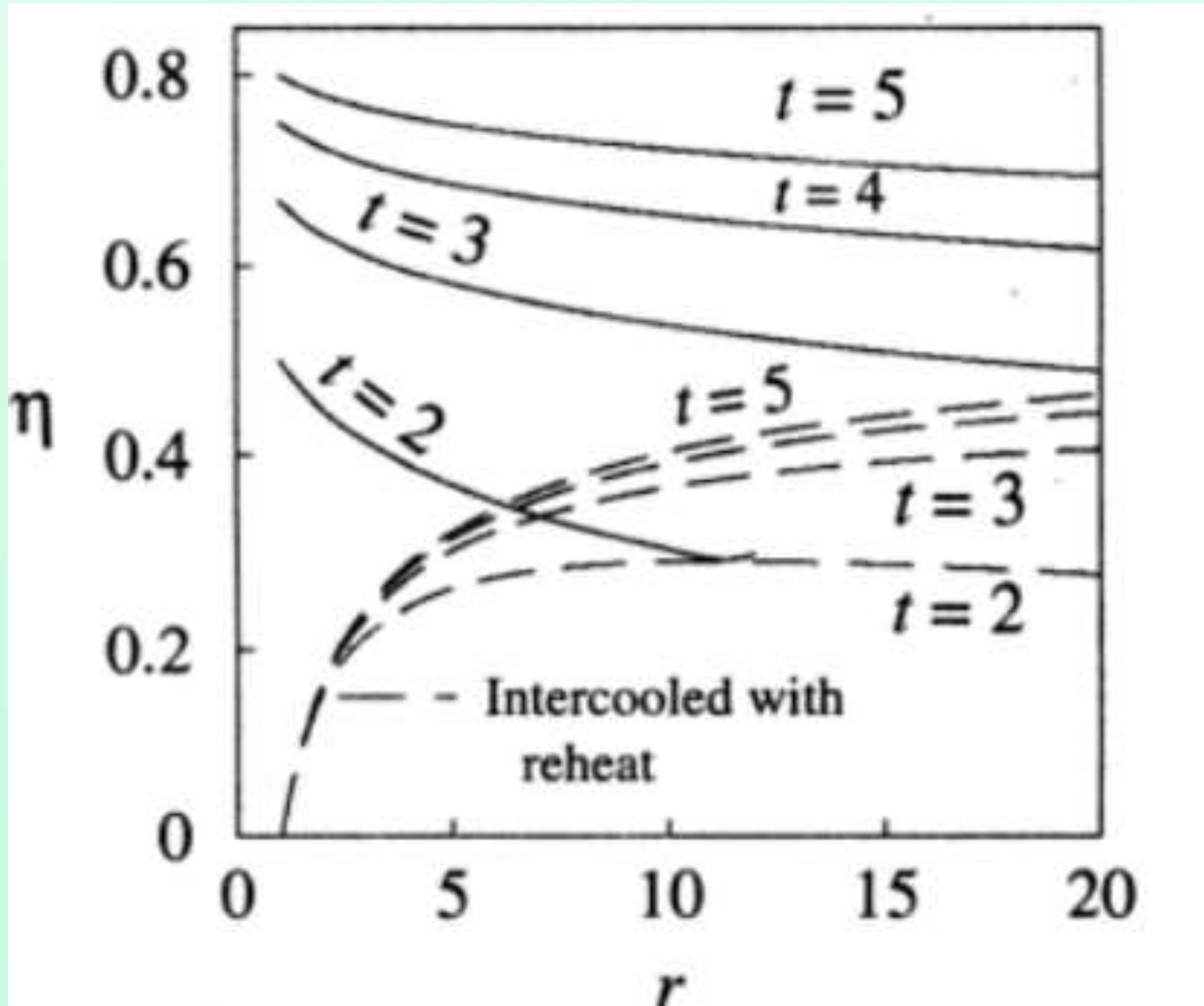
Intercooled, Reheat & Heat Exchange: Work



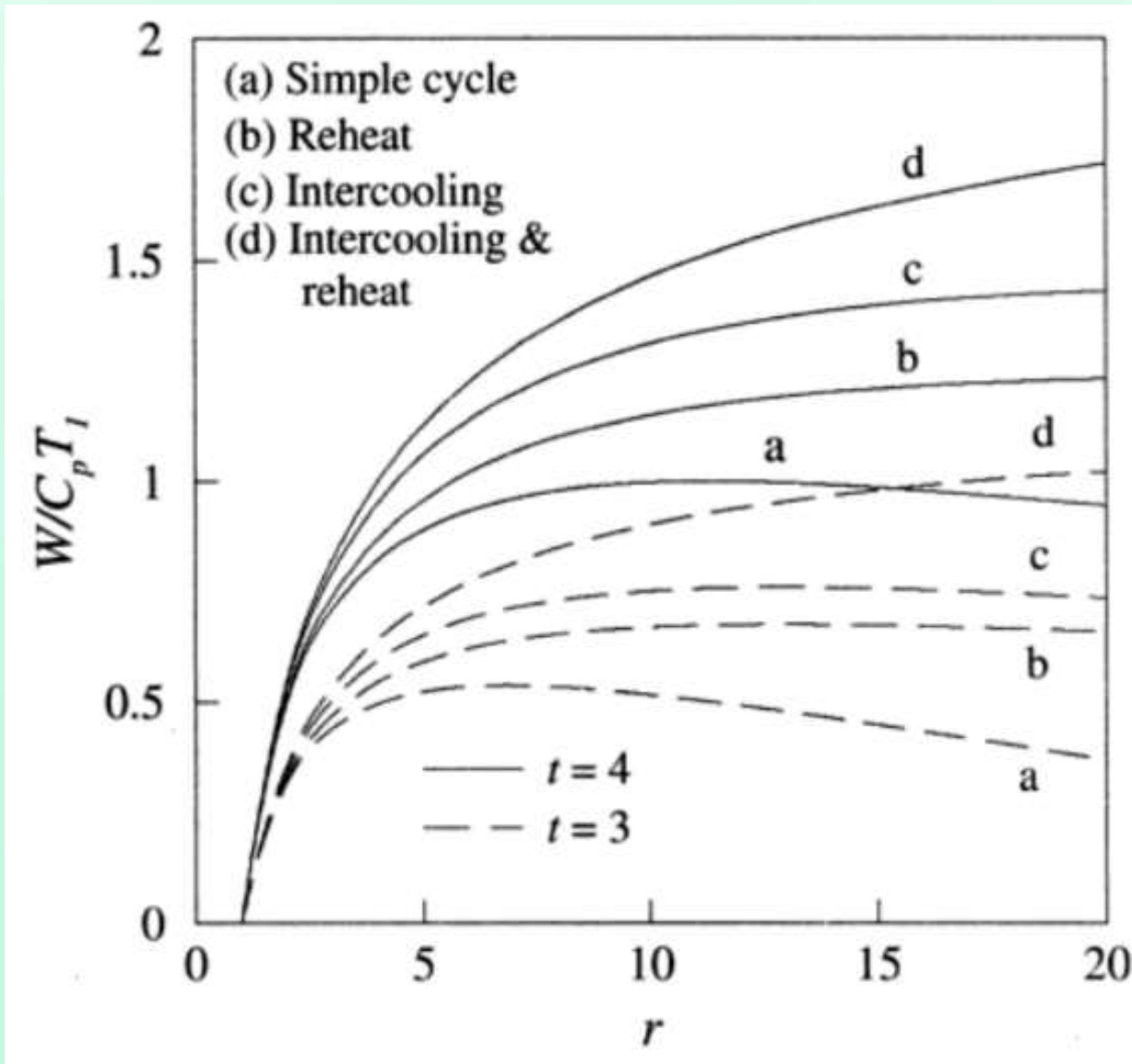
$$\frac{W_{\max}}{c_p T_1} = 2 \left(t - \frac{t}{\sqrt{c}} - \sqrt{c} + 1 \right)$$



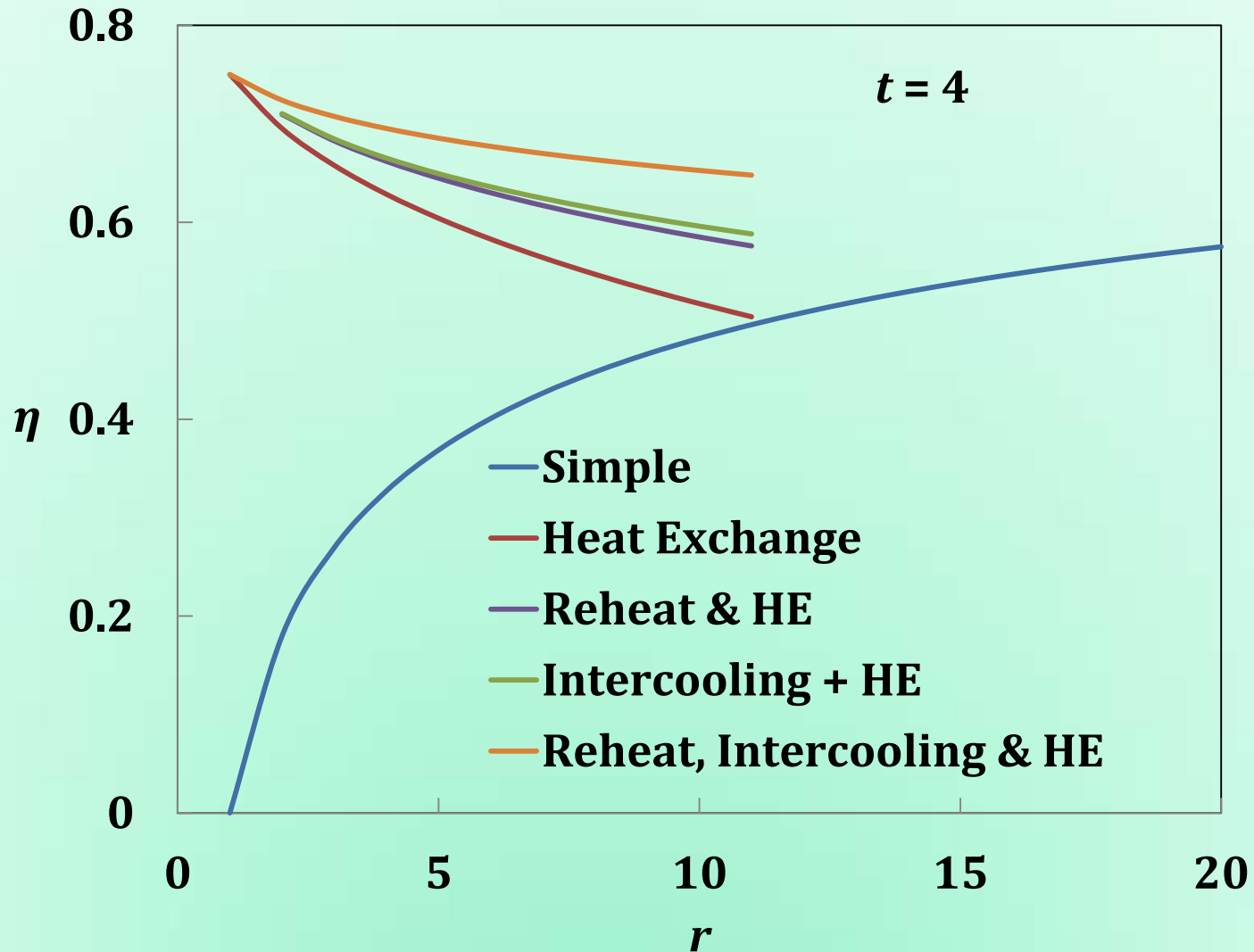
Intercooled, Reheat & Heat Exchange: Efficiency



Comparison: Specific Work Output



Comparison: Efficiency



Comparison ($r = 4, t = 3$)



S.No.	Addition to simple cycle	Effect on	
		η	$\frac{W}{C_p T_1}$
1.	Heat exchange	+50.0	No change
2.	Intercooling	- 6.50	+10.2
3.	Reheat	-10.4	+24.5
4.	Reheat and heat exchange	+66.7	+24.5
5.	Intercooling and heat exchange	+68.0	+10.2
6.	Reheat and intercooling	-18.2	+34.7
7.	Reheat, intercooling and heat exchange	+80.0	+34.7

Problem: Ideal Cycle Analysis



A gas turbine cycle has a heat exchanger. Air enters the compressor at a temperature and pressure of 300 K and 1 bar and discharges at 475 K and 5 bar. After passing through the heat exchanger the air temperature increases to 655 K. The temperature of air entering and leaving the turbine are 870°C and 450°C. Assuming no pressure drop through the heat exchanger, compute:

1. the work output per kg of air
2. the efficiency of the cycle
3. the work required to drive the compressor

Assume $C_p = 1.005$ kJ/kg K.

Ans: 246.2 kJ/kg, 50.2%, 175.9 kJ/kg

Problem: Ideal Cycle Analysis



Compute the efficiency of a Joule cycle if the temperature at the end of combustion is 2000 K and the temperature and pressure before compression is 350 K and 1 bar. The pressure ratio is 1.3.

Ans: 7.2%

Calculate the improvement in the efficiency when a heat exchanger is added to the simple cycle.

Ans: 81%, 11 times improvement

Do the same analysis for a different pressure ratios: $r = 5, 10, 20$.

Ans: 36.9%, 72%; 48%, 66%; 57.5%, 58.8%

Problem: Ideal Cycle Analysis



An ideal open cycle gas turbine plant using air operates in an overall pressure ratio of 4 and between temperature limits of 300 K, 1000 K. Evaluate the work output and thermal efficiency for:

1. Basic cycle
2. Basic cycle with heat exchanger
3. Basic cycle with two stage intercooled compressor
4. Basic cycle with heat exchanger and two-stage intercooled compressor

Assume the constant value $C_p = 1$ kJ/kg K, $C_v = 0.717$ kJ/kg K, optimum stage pressure ratios, perfect intercooling and perfect regeneration.

Ans: 180.4 kJ/kg, 32.4%, 180.4 kJ/kg, 55.6%; 192.3 kJ/kg, 30.3%, 192.3 kJ/kg, 59.3%

Applied Thermodynamics - II



Gas Turbines – Shaft Power Real Cycles

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- High velocity in turbomachinery: ΔKE cannot be ignored.
- Compression and expansion are irreversible adiabatic processes: entropy increases.
- Fluid friction: pressure losses in CC, HE, inlet and outlet ducts.
- No perfect heat exchange keeping the size in mind.
- More work for compression due to bearing, 'windage' friction in the transmission between compressor and turbine, and to drive ancillary components such as fuel and oil pumps.
- C_p and γ vary throughout due to changes of T , chemical composition.
- η for ideal cycle is unambiguous. Open cycle with internal combustion? Express the performance in terms of fuel consumption per unit net work output, Specific Fuel Consumption (*SFC*).
- Mass flow is assumed to be the same. Bleeding from compressor to cool turbine (1 to 2%) is compensated by the addition of fuel.



Stagnation Properties

- KE terms in the steady flow energy equation can be accounted for, implicitly by making use of stagnation enthalpy.
- h_0 is the enthalpy which a gas stream of h and c would possess when brought to rest adiabatically and without work transfer.

$$(h_0 - h) + \frac{1}{2}(0 - c^2) = 0$$

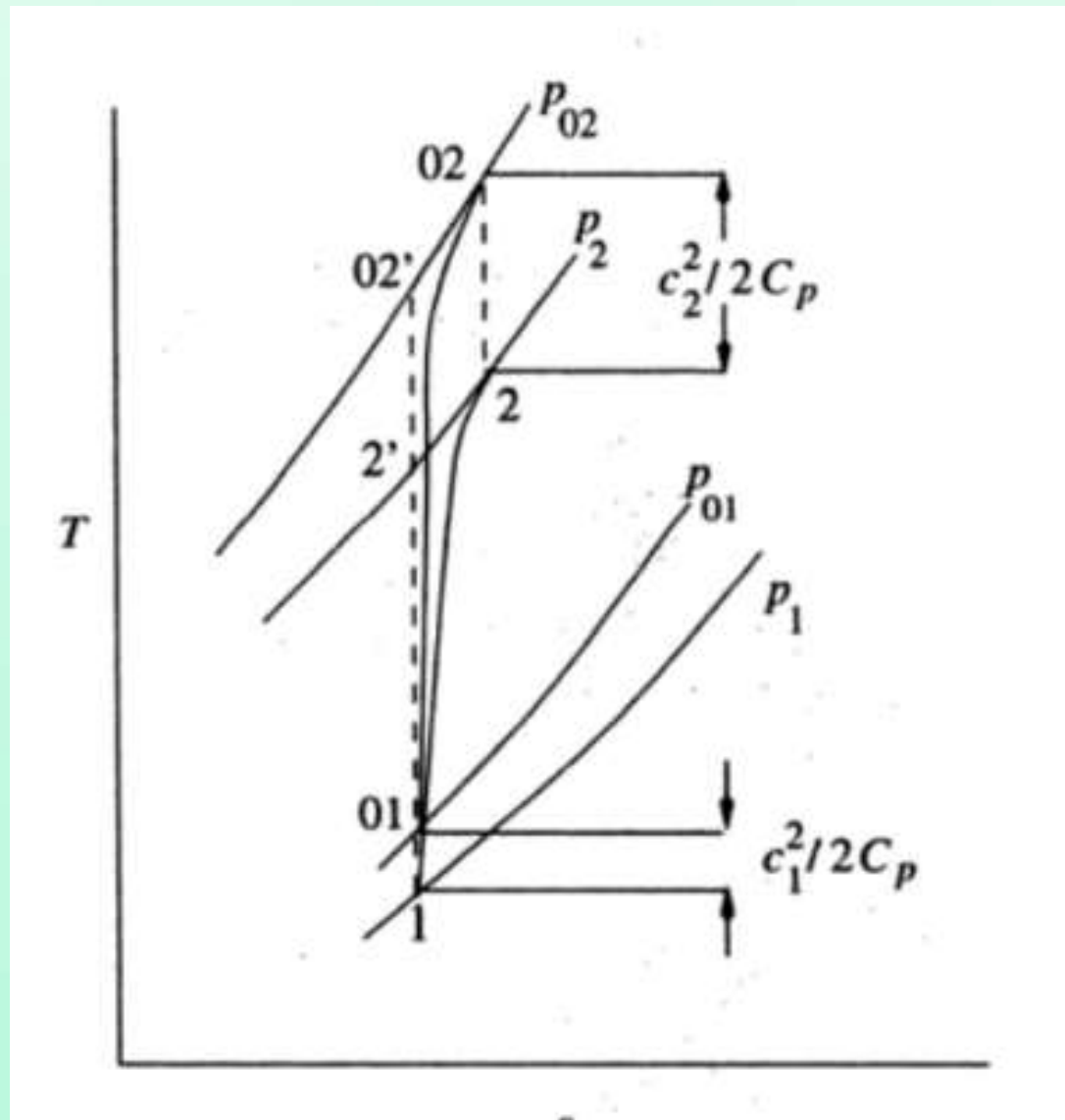
$$h_0 = h + \frac{c^2}{2}$$

$$T_0 = T + \frac{c^2}{2C_p}$$

static

dynamic temperature

Stagnation Properties: Compression



Adiabatic compression, the energy equation becomes:

$$W = -C_p \left[\underbrace{(T_2 - T_1)}_{\text{static component}} + \underbrace{\left(\frac{c_2^2}{2C_p} - \frac{c_1^2}{2C_p} \right)}_{\text{dynamic component}} \right]$$

$$W = \underbrace{-C_p(T_{02} - T_{01})}_{\text{stagnation}}$$

Similarly for a heating process without work transfer

$$Q = C_p(T_{02} - T_{01})$$

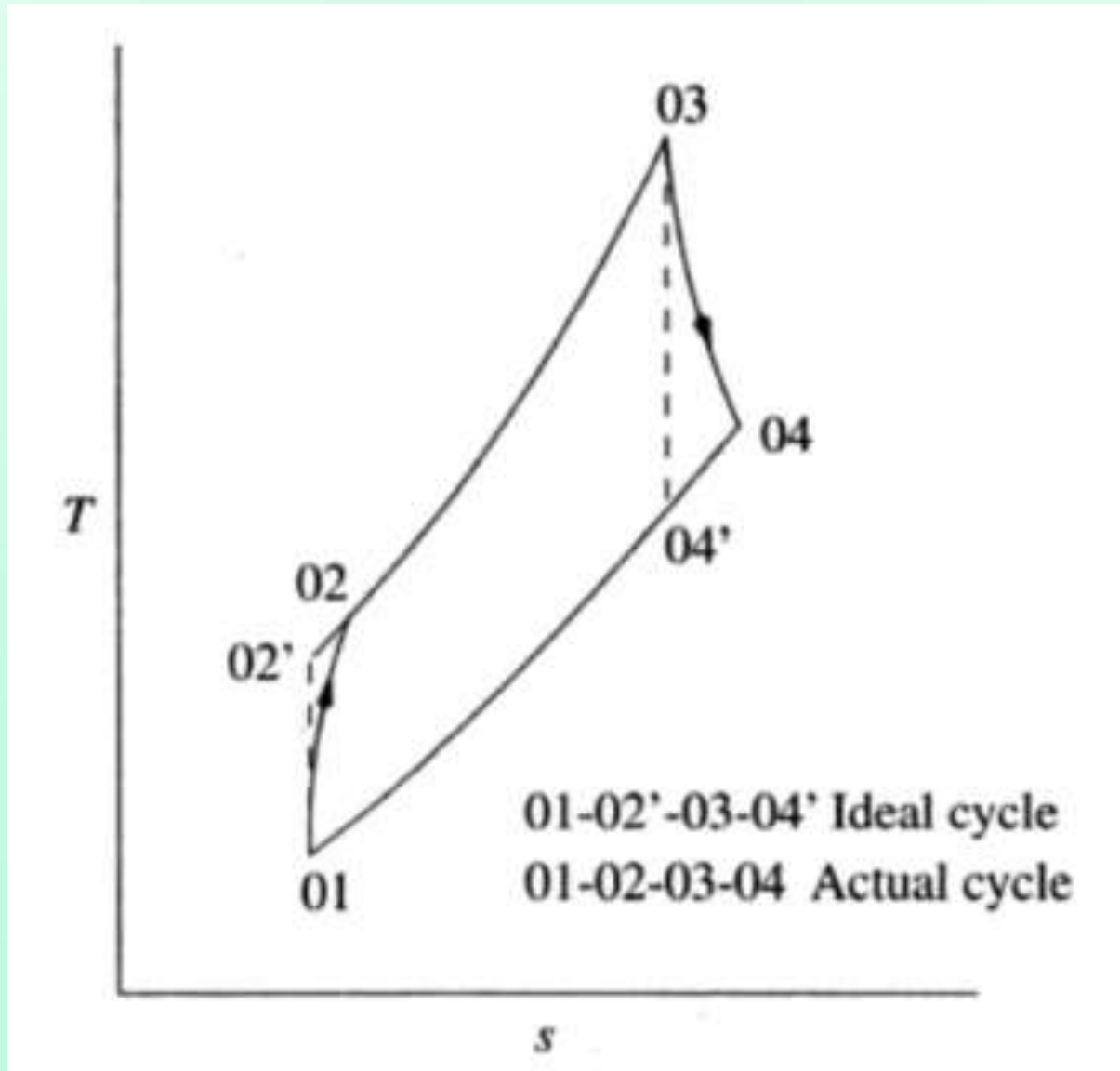


When a gas is brought to rest, adiabatically and reversibly:

$$\frac{p_0}{p} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}}$$

The effect of the inclusion of velocity in the calculation: Refer to stagnation conditions (h_0, T_0, p_0) but not static conditions (h, T, p) as we did in the ideal cycle analysis.

Compressor and Turbine Efficiency





$$\eta_c = \frac{\text{Work required for isentropic compression}}{\text{Actual compression work input}}$$

$$= \frac{h_{02'} - h_{01}}{h_{02} - h_{01}} = \frac{T_{02'} - T_{01}}{T_{02} - T_{01}}$$

$$T_{02} - T_{01} = \frac{T_{01}}{\eta_c} \left[r_c^{(\gamma-1)/\gamma} - 1 \right]$$

$$W_{c_{act}} = \frac{C_p T_{01}}{\eta_c} \left[r_c^{(\gamma-1)/\gamma} - 1 \right]$$



$$\eta_t = \frac{\text{Actual turbine work output}}{\text{Isentropic turbine work output}}$$

$$= \frac{h_{03} - h_{04}}{h_{03} - h_{04'}} = \frac{T_{03} - T_{04}}{T_{03} - T_{04'}}$$

$$T_{03} - T_{04} = \eta_t T_{03} \left[1 - \frac{1}{r_t^{(\gamma-1)/\gamma}} \right]$$

$$W_{t_{act}} = \eta_t C_p T_{03} \left[1 - \frac{1}{r_t^{(\gamma-1)/\gamma}} \right]$$



Losses due to friction & turbulence occurs throughout the whole plant.

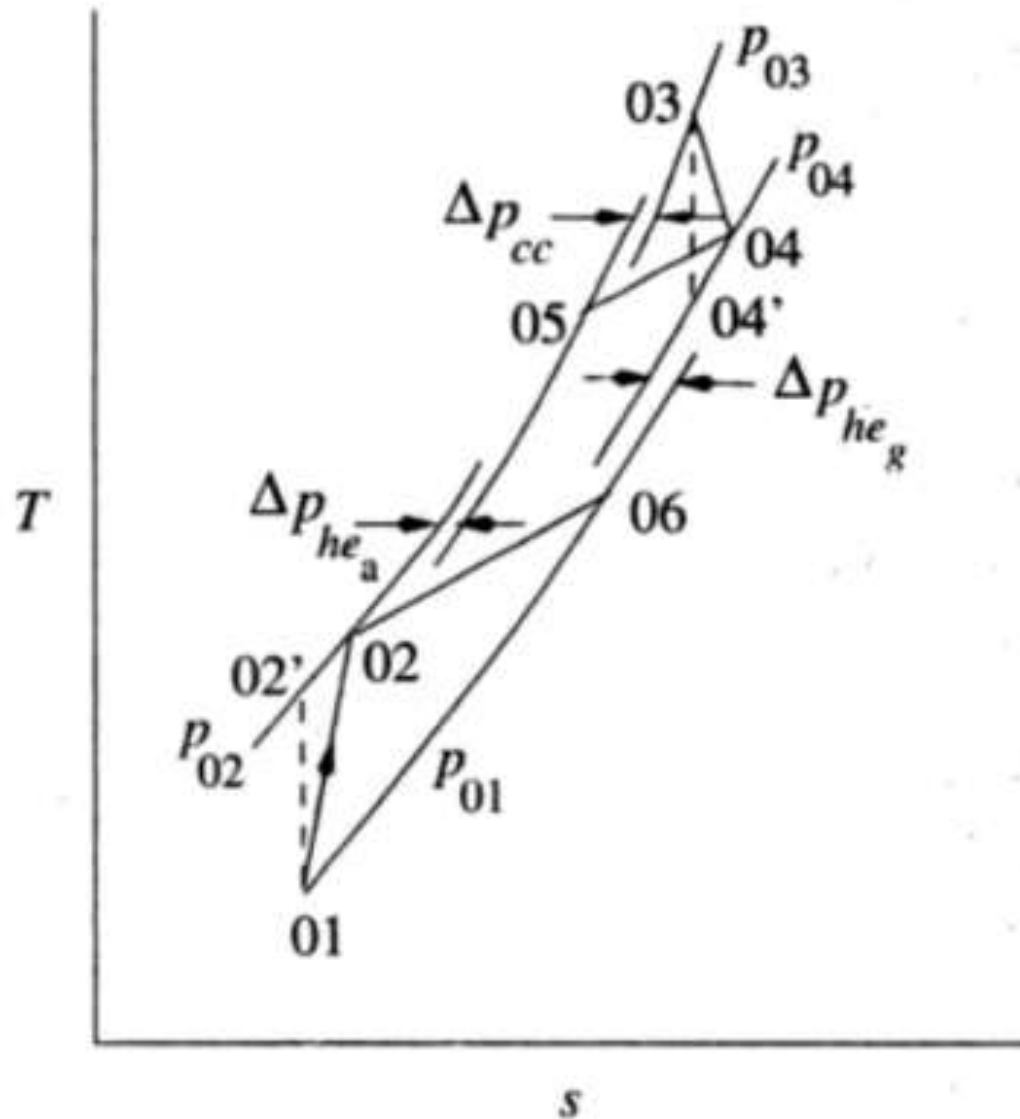
1. Air side intercooler loss
2. Air side heat exchanger loss
3. Combustion chamber loss (both main and reheat)
4. Gas side heat exchanger loss
5. Duct losses between components and at intake and exhaust

The pressure losses have the effect of decreasing r_t relative to r_c

Reduces net work output from the plant

Gas turbine cycle is very sensitive to irreversibilities:

Δp significantly effects the cycle performance





$$p_{03} = p_{02} - \Delta p_{cc} - \Delta p_{hea}$$

$$p_{04} = p_a + \Delta p_{heg}$$

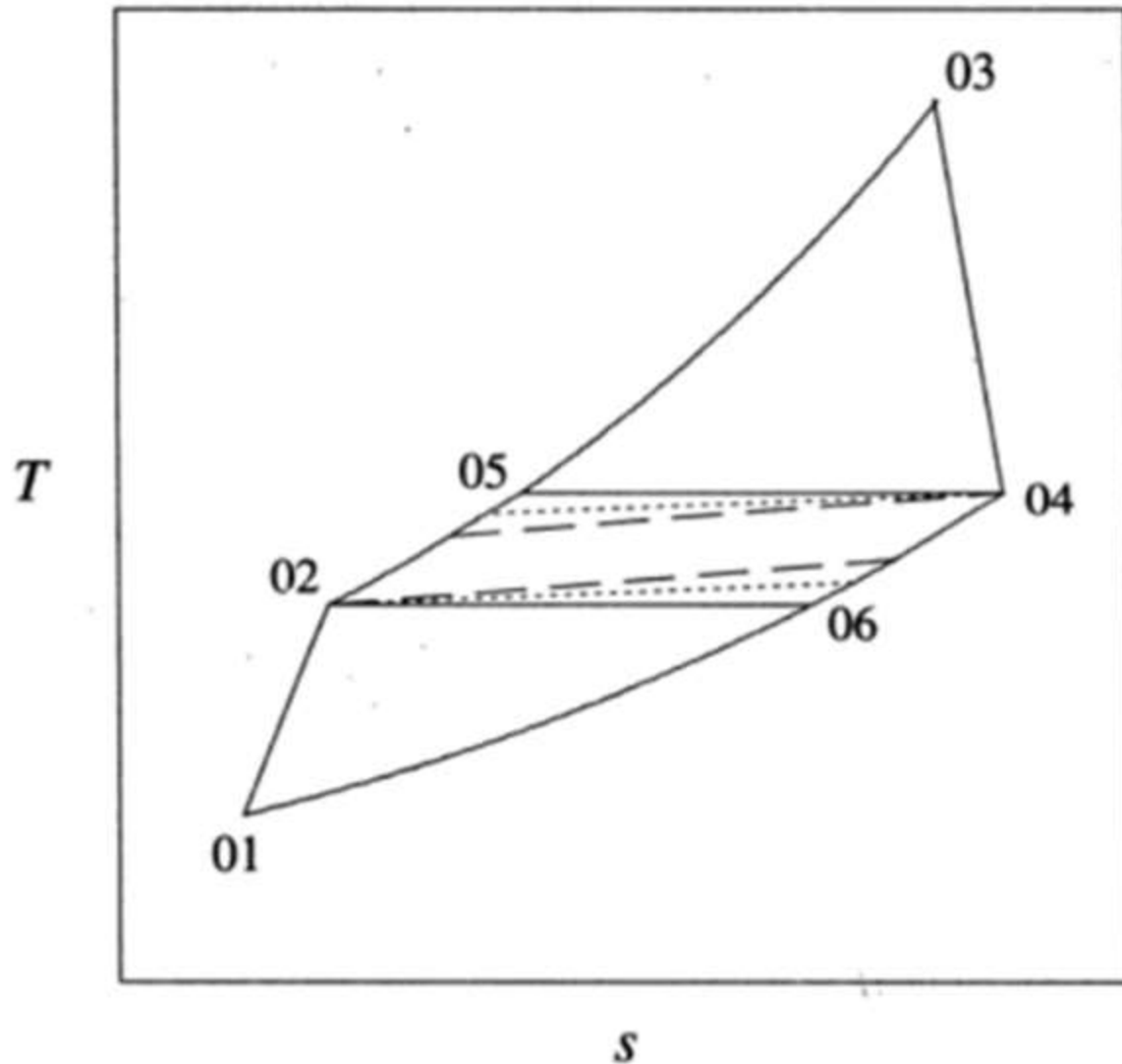
The turbine inlet pressure is then found from:

$$p_{03} = p_{02} \left(1 - \frac{\Delta p_{cc}}{p_{02}} - \frac{\Delta p_{hea}}{p_{02}} \right)$$

Pressure losses minimized by large CC with consequent low velocities.

Typically $\frac{\Delta p_{cc}}{p_{02}} \approx 2$ to 3% for a large industrial unit and 6 to 8% for an
aero engine

Heat Exchanger Effectiveness





Heat transfer with small dT requires infinite area

$$\dot{m}_a C_{p_a} (T_{05} - T_{02}) = \dot{m}_g C_{p_g} (T_{04} - T_{06})$$

$$\epsilon = \frac{T_{05} - T_{02}}{T_{04} - T_{02}}$$

Larger areas \Rightarrow larger ϵ



$$\dot{m}_g = \dot{m}_a + \dot{m}_f$$

$$\frac{\dot{m}_g}{\dot{m}_a} = 1 + \frac{\dot{m}_f}{\dot{m}_a} = 1 + f$$

However, this increase is compensated by the bleeding compressed air to turbine cooling.



C_{p_a} is independent of P within the operating limits but varies with T

$$C_{p_{300K}} = 1.005 \text{ kJ/kg K}$$

$$C_{p_{1000K}} = 1.140 \text{ kJ/kg K}$$

An increase of about 13.4%

However, γ decreases with T

Recommended: a C_{p_a} for compressor & C_{p_g} for heating and expansion



Bearing friction, windage amounts to 10% of the W_c

$$W_c = \frac{1}{\eta_{mech}} C_{pa} (T_{02} - T_{01})$$



$$\eta_b = \frac{\text{enthalpy released}}{\text{available entalpy of fuel}} = 0.98$$



$$\dot{m}_f \eta_b \Delta H_{rp} = (\dot{m}_f + \dot{m}_a) C_{pg} (T_{03} - T_{02})$$

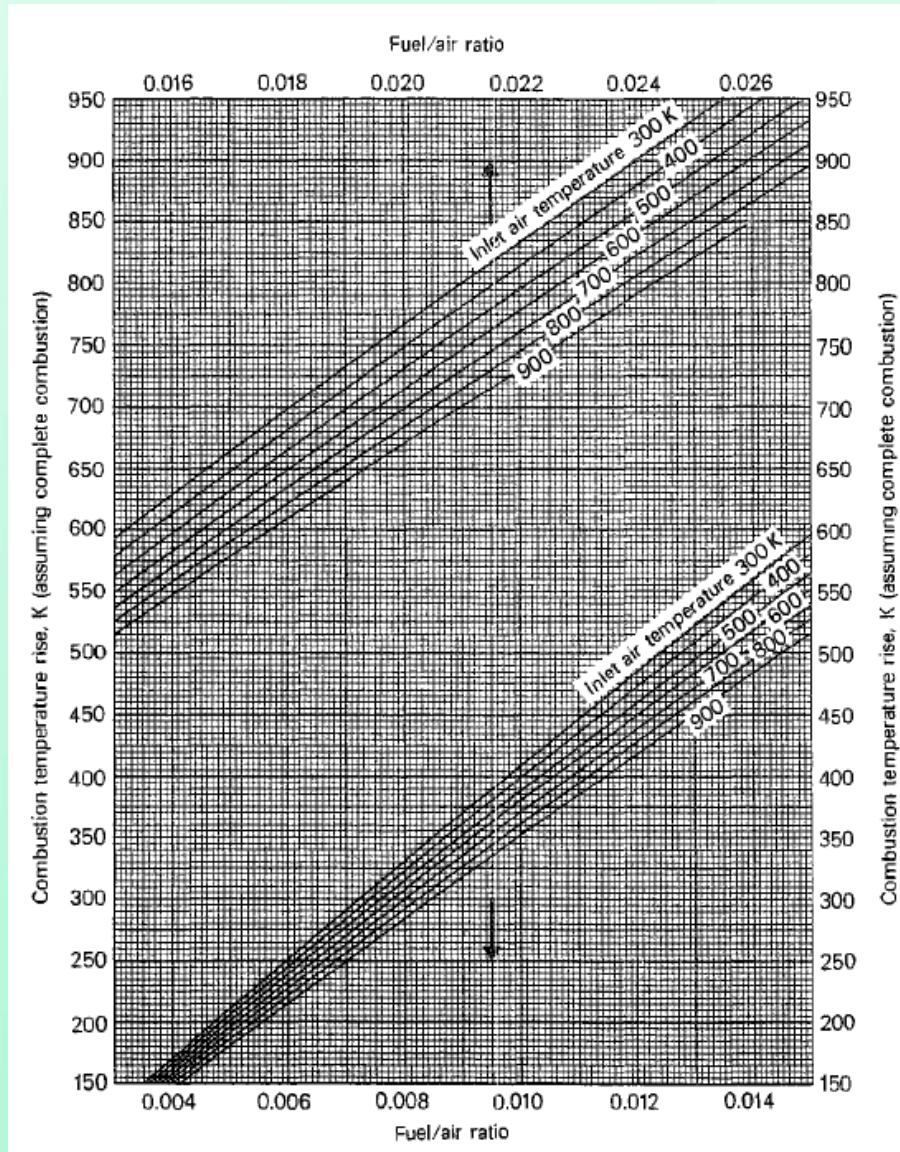
ΔH_{rp} is the enthalpy of reaction for unit mass at 25°C

Lower calorific value

$$f \eta_b \Delta H_{rp} = C_{pg} (T_{03} - T_{02})$$

$$C_{pg} = \text{function}(T, \text{species composition})$$

Iteratively solve for f and C_{pg}



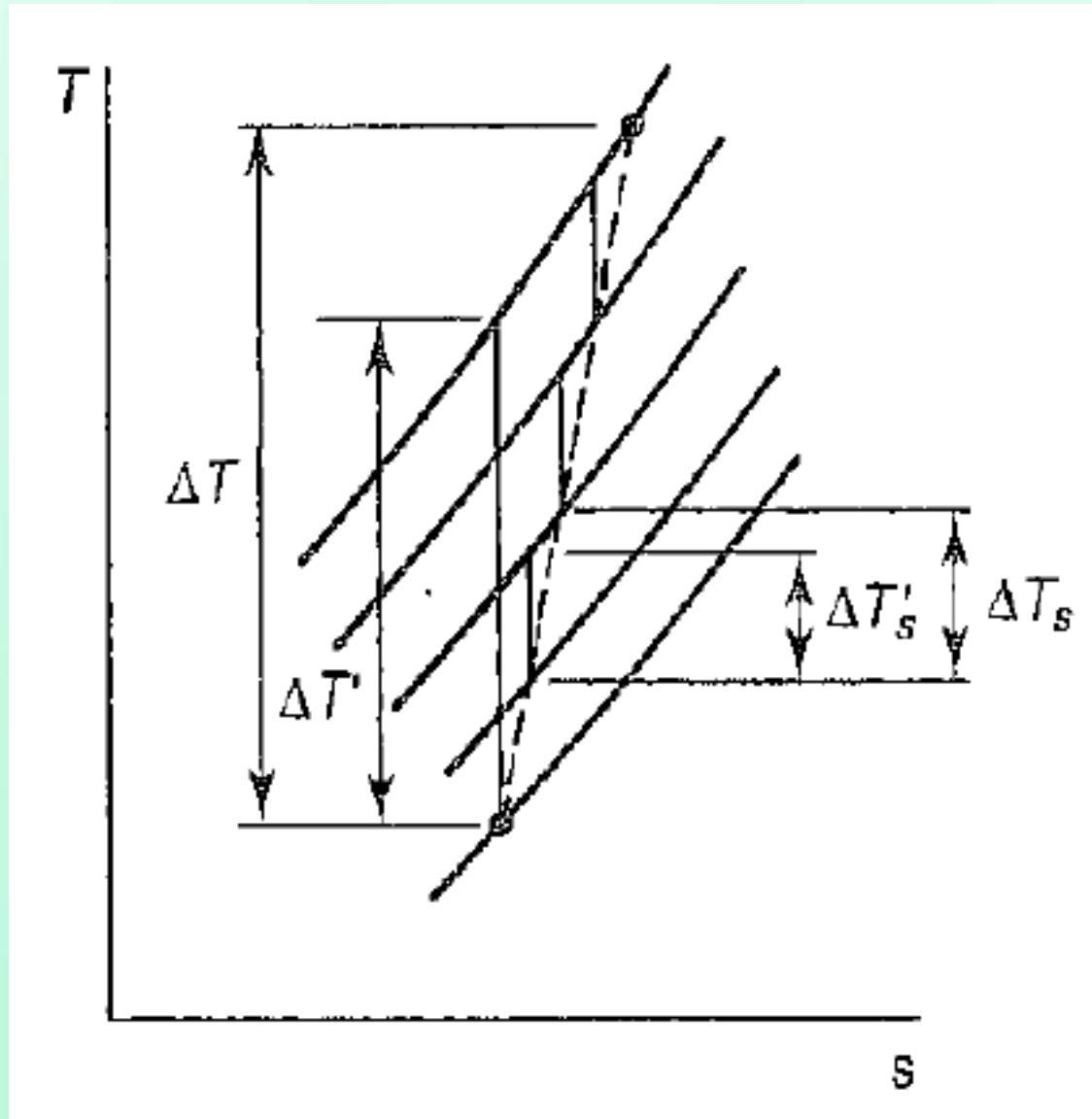


$$SFC = \frac{f}{W_N}$$

$$SFC = \frac{3600 f}{W_N} \text{ kg/kW h}$$

$$\eta = \frac{W_N}{f CV}$$

Polytropic Efficiency





$$\frac{\eta_s}{\eta_c} = \frac{\sum \Delta T'_s}{\Delta T'}$$

- $\eta_c < \eta_s$ and this difference increases with number of stages (r).
- Meaning work is required due to 'preheat' effect.
- Similarly for a turbine $\eta_t > \eta_s$. Frictional 'reheating' in one stage is partially recovered as work in the next.
- Polytropic efficiency is the isentropic efficiency of an elemental stage in the process such that it is constant throughout the whole process.

$$\eta_{sc} = \frac{dT'}{dT} = \text{constant}$$

$$\frac{T}{p^{(\gamma-1)/\gamma}} = \text{constant}$$



$$\frac{dT'}{T} = \frac{\gamma - 1}{\gamma} \frac{dp}{p}$$

$$\eta_{sc} = \frac{\ln(p_2/p_1)^{(\gamma-1)/\gamma}}{\ln(T_2/T_1)}$$

η_{cs} computed for given values

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma \eta_{sc}}$$

$$\eta_c = \frac{(p_2/p_1)^{(\gamma-1)/\gamma} - 1}{(p_2/p_1)^{(\gamma-1)/\gamma \eta_{sc}} - 1}$$



$$T_{02} - T_{01} = T_{01} \left[\left(\frac{p_{02}}{p_{01}} \right)^{(n-1)/n} - 1 \right]$$

$$(n - 1)/n = (\gamma - 1)/\gamma \eta_{sc}$$

For Turbine, $\eta_{st} = \frac{dT}{dT'} = \text{constant}$

$$T_{03} - T_{04} = T_{03} \left[1 - \frac{1}{\left(\frac{p_{02}}{p_{01}} \right)^{(n-1)/n}} \right]$$

$$(n - 1)/n = \eta_{st}(\gamma - 1)/\gamma$$



For Turbine, $\eta_{st} = \frac{dT}{dT'} = \text{constant}$

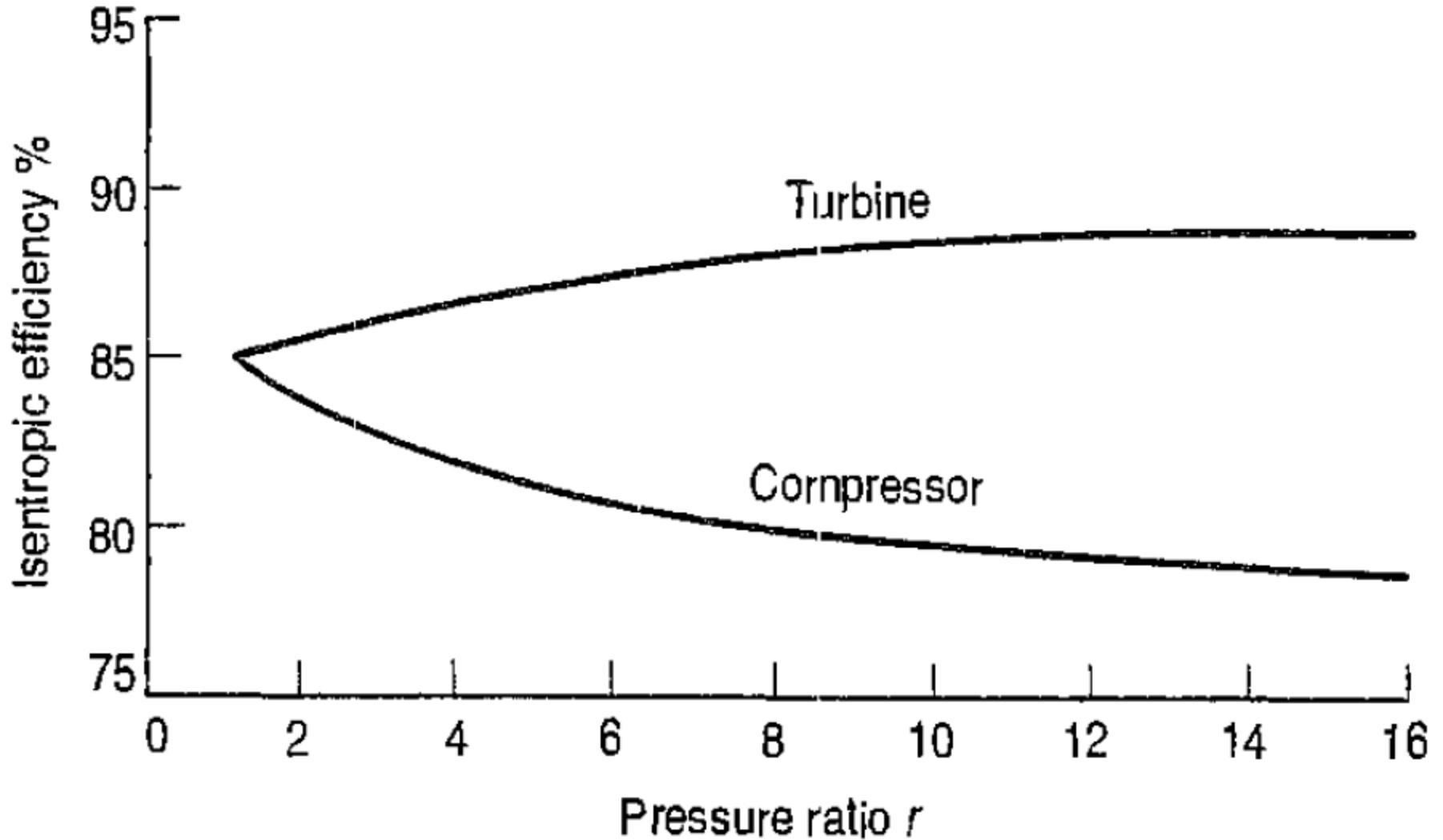
$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4} \right)^{\eta_{st}(\gamma-1)/\gamma}$$

$$\eta_c = \frac{(p_2/p_1)^{(\gamma-1)/\gamma} - 1}{(p_2/p_1)^{\eta_{st}(\gamma-1)/\gamma} - 1}$$

$$T_{03} - T_{04} = T_{03} \left[1 - \frac{1}{\left(\frac{p_{02}}{p_{01}} \right)^{(n-1)/n}} \right]$$

$$(n - 1)/n = \eta_{st}(\gamma - 1)/\gamma$$

Polytropic Efficiency

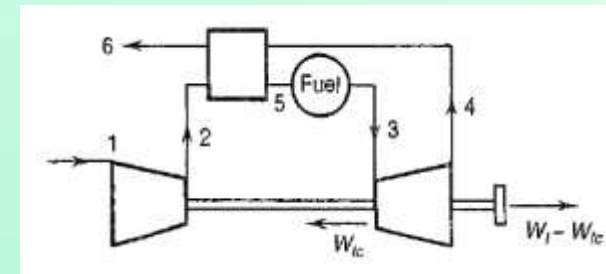


Problem: Real Cycle Analysis



Determine the specific work output, SFC , η for a heat-exchange cycle with the following specifications:

Compressor pressure ratio	4.0
Turbine inlet temperature	1100 K
Isentropic efficiency of compressor, η_c	0.85
Isentropic efficiency of turbine, η_t	0.87
Mechanical transmission efficiency, η_m	0.99
Combustion efficiency, η_b	0.99
Heat-exchanger effectiveness, ϵ	0.80
Pressure losses:	
Combustion chamber, Δp_{cc}	2% comp. deliv. press.
Heat-exchanger air-side, Δp_{ha}	3% comp. deliv. press.
Heat-exchanger gas-side, Δp_{hg}	0.04 bar
Ambient conditions, p_a, T_a	1 bar, 288 K



Problem: Real Cycle Analysis



Hint

Compute p_{02} , T_{02} at compressor exit

Compute W_c (using η_{mech})

Compute p_{03} , p_{04} using Δp values

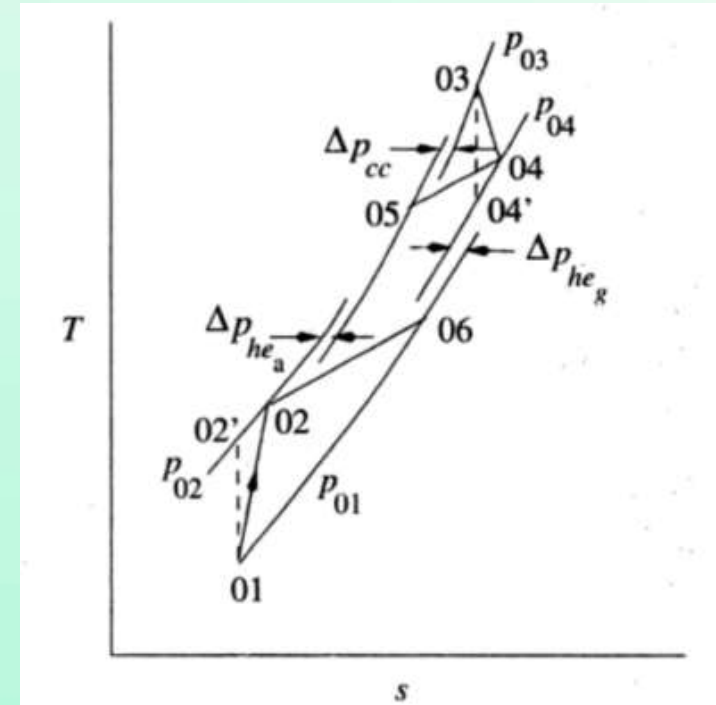
Compute T_{04} , W_t , then W_{Nt}

Using ϵ , find T_{05}

Compute W_N

Using the chart, find f corresponding to $T_{03} - T_{05}$

Compute SFC , η



Ans: 137 kJ/kg, 0.253 kg/kW h, 33.1%

Problem: Real Cycle Analysis



An oil gas turbine installation consists of a compressor, a combustion chamber and turbine. The air taken in at a pressure of 1 bar and 30°C is compressed to 6 bar, with an isentropic efficiency of 87%. Heat is added by the combustion of fuel in combustion chamber to raise the temperature to 700°C. The efficiency of the turbine is 85%. The calorific value of the oil used is 43.1 MJ/kg. Calculate for an air flow of 80 kg/min

1. the air/fuel ratio of the turbine gases
2. the final temperature of exhaust gases
3. the net power of installation
4. The overall thermal efficiency of the installation

Assume $C_{pa} = 1.005$ kJ/kg K, $\gamma_a = 1.4$, $C_{pg} = 1.147$ kJ/kg K, $\gamma_g = 1.33$.

Ans: 86 kg/kg, 676.2 K, 147.2 kW, 22%

Problem: Real Cycle Analysis



At design speed the following data apply to a gas turbine set employing a separate power turbine, heat exchanger, reheater and intercooler between two-stage compression.

$C_{pa} = 1.005 \text{ kJ/kg K}$, $\gamma_a = 1.4$,
 $C_{pg} = 1.147 \text{ kJ/kg K}$, $\gamma_g = 1.33$.
Calorific value of fuel is 42 MJ/kg

Pressure loss in each side
of heat exchanger is 0.1 bar .

Efficiency of compression in each stage:	80%
Isentropic efficiency of compressor turbine:	87%
Isentropic efficiency of power turbine:	80%
Transmission efficiency:	99%
Pressure ratio in each stage of compression:	2:1
Pressure loss in intercooler:	0.07 bar
Temperature after intercooling:	300 K
Thermal ratio of heat exchanger:	0.75
Pressure loss in combustion chamber:	0.15 bar
Combustion efficiency of reheater:	98%
Maximum cycle temperature:	1000 K
Temperature after reheating:	1000 K
Air mass flow:	25 kg/s
Ambient air temperature:	15°C
Ambient air pressure:	1 bar

Applied Thermodynamics - II



Gas Turbines – Jet Propulsion Cycles

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- Jet propulsion is produced, *wholly* (turbojet) or *partially* (turboprop), as a result of expansion of gas in a propelling nozzle
- Effect of forward speed and altitude on the performance of propulsion engines
- Application of Newton's laws of motion
- Any working fluid can be used



1. A heated and compressed atmospheric air, mixed with products of combustion, air temperature rises to the desired value.
 - Thermal jet
 - **Air breathing engines**
2. Fuel and oxidizer are carried with the system itself, fuel-oxidant mixture is propellant.
 - No air is used. Jet is *Rocket jet*, the equipment wherein the chemical reaction takes place is *Rocket motor*
 - **Rocket engine**

Net Thrust

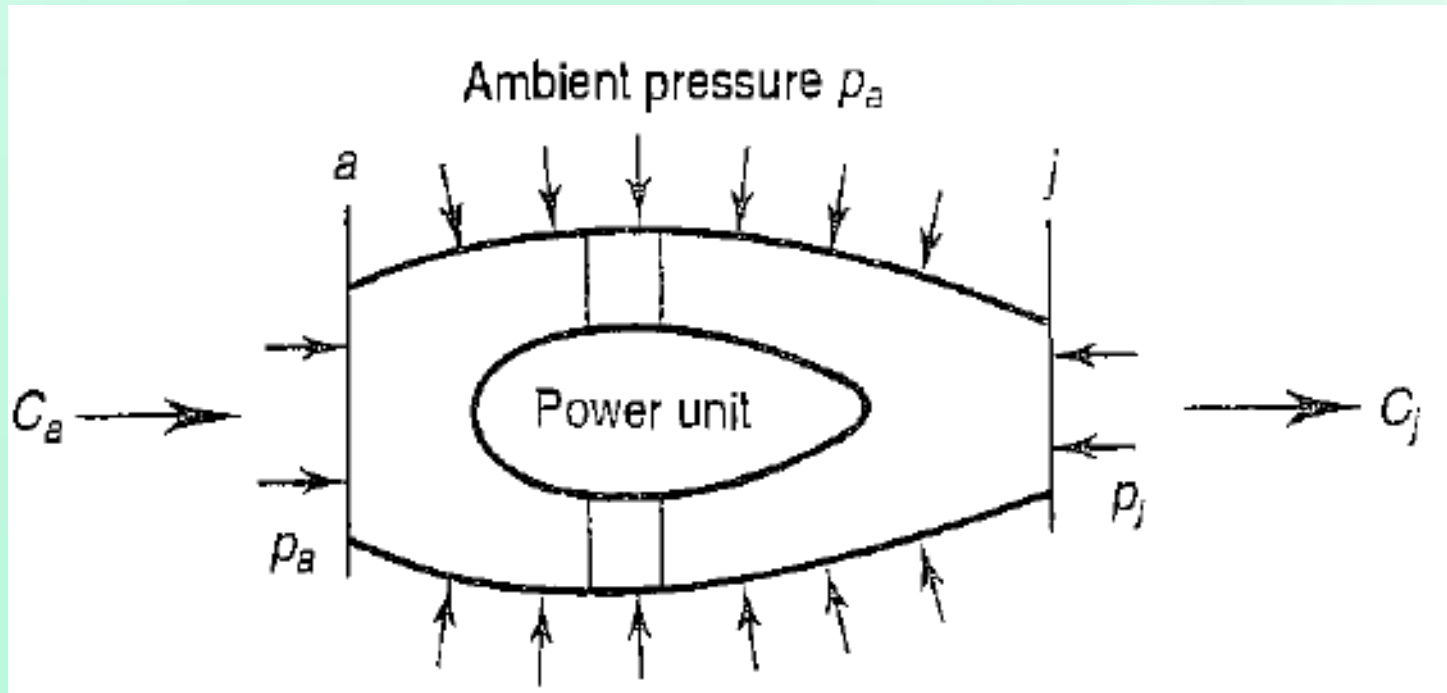


Net thrust = Momentum thrust + Pressure thrust

$$F = m(C_j - C_a) + A_j(P_j - P_a)$$

mC_j is gross momentum thrust

mC_a is intake momentum drag





Ratio of the useful propulsive energy or thrust power (FC_a) to the sum of that energy and the unused kinetic energy of the jet

The unused KE of the jet relative to the earth is $m(C_j - C_a)^2/2$

$$\eta_p = \frac{mC_a(C_j - C_a)}{mC_a(C_j - C_a) + m(C_j - C_a)^2/2}$$

$$\eta_p = \frac{2}{1 + C_j/C_a}$$

- F is maximum for $C_a = 0$ (static conditions), but $\eta_p = 0$
- η_p is maximum for $C_j/C_a = 1$, but $F = 0$

$$C_j > C_a$$



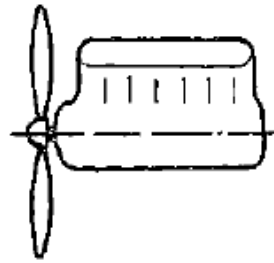
In the order of increasing mass flow and decreasing jet velocity:

1. Ramjet engine
 2. Pulse jet engine
 3. Turbojet engine
 4. Turboprop engine
- Higher cruising speed for ramjet while lower for turbojet
 - Selection depends on: Cruising speed, desired range of the aircraft and maximum rate of climb

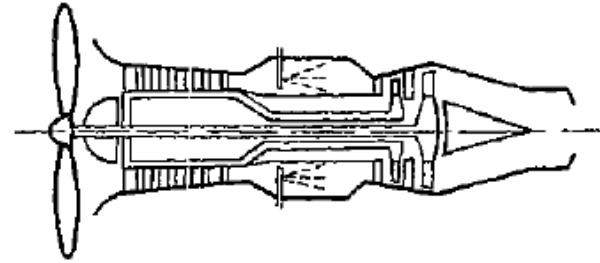
Another classification:

- A. Pilotless operation (1, 2)
- B. Piloted operation (3, 4)

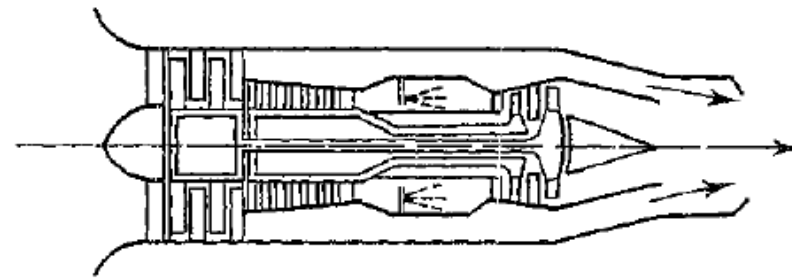
Classification



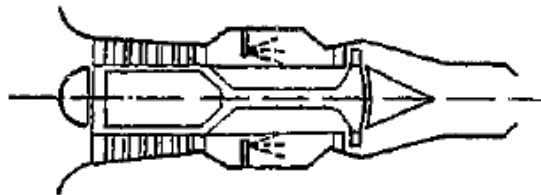
(a) Piston engine



(b) Turboprop engine



(c) Turbofan engine

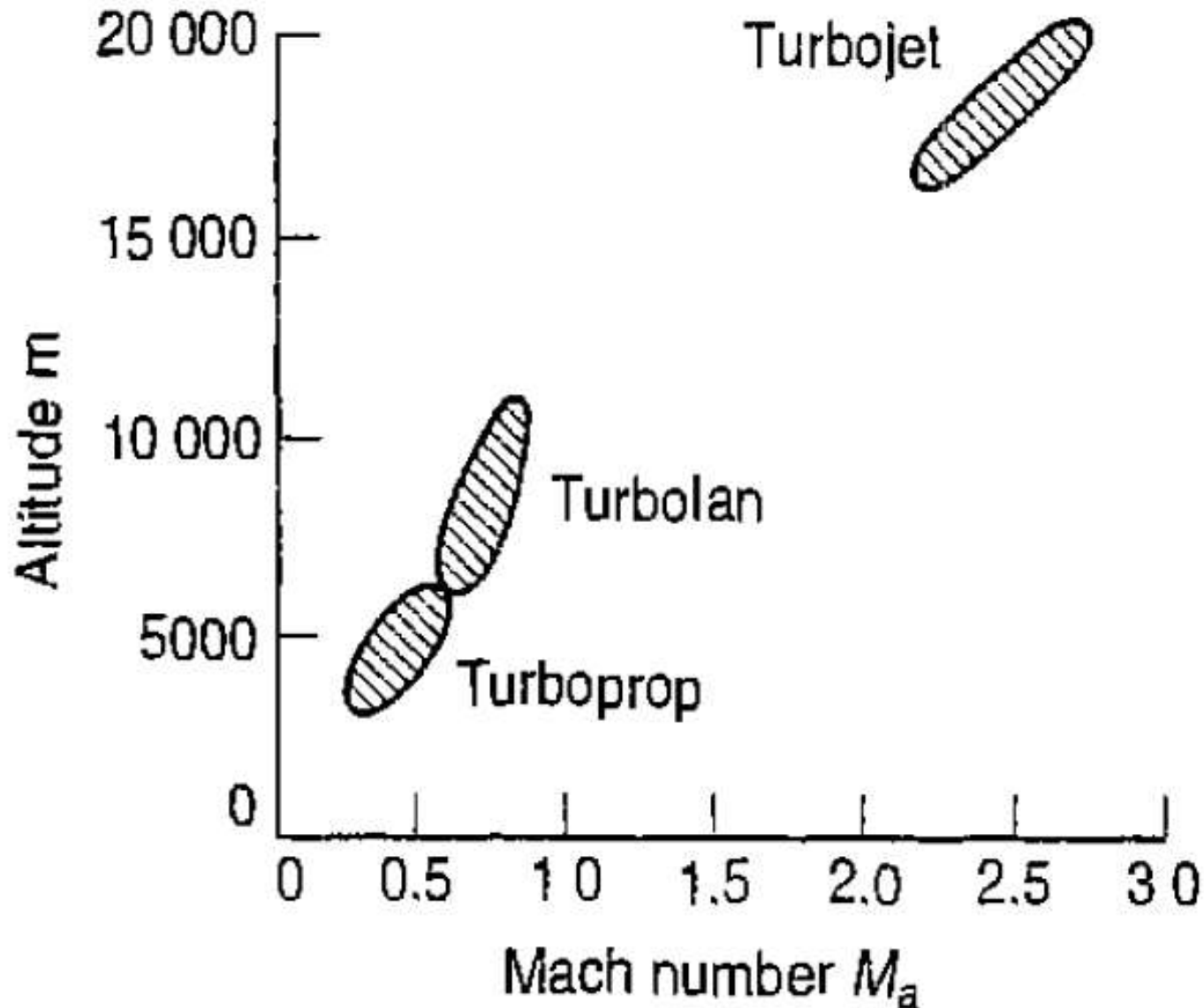


(d) Turbojet engine



(e) Ramjet engine

Classification





The rate of energy supplied in the fuel ($m_f Q_{net}$) is converted into:

potentially useful KE for propulsion $m(C_j^2 - C_a^2)/2$

together with unusable enthalpy in the jet $mC_p(T_j - T_a)$

$$\eta_e = \frac{m(C_j^2 - C_a^2)/2}{m_f Q_{net}}$$



Overall efficiency is the ratio of the useful work done in overcoming drag to the energy in the fuel supplied:

$$\eta_o = \frac{m C_a (C_j - C_a)}{m_f Q_{net}} = \frac{F C_a}{m_f Q_{net}}$$

$$\eta_o = \eta_p \eta_e$$

η of an aircraft is inextricably linked to the aircraft speed



SFC for an aircraft engine is the fuel consumption per unit thrust (kg/h N)

$$SFC = \frac{m_f}{F}$$

$$\eta_o = \frac{C_a}{SFC} \frac{1}{Q_{net}}$$

With a given fuel, the value of Q_{net} is constant.

$\eta_o \propto C_a/SFC$ while it is $1/SFC$ for shaft power units



Specific thrust is the thrust per unit mass flow of air (Ns/kg)

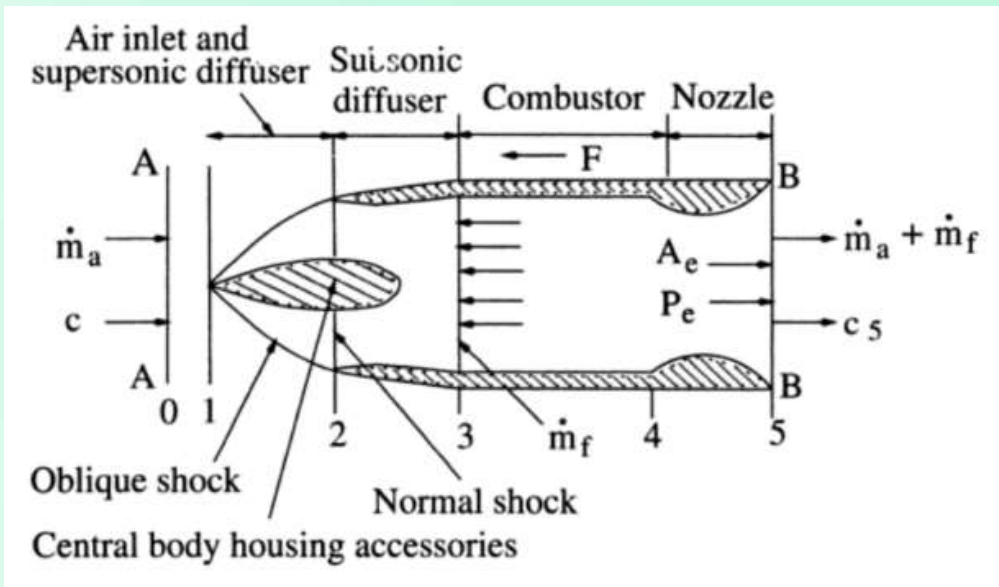
$$F_s = \frac{F}{m_a}$$

$$SFC = \frac{f}{F_s}$$

Ramjet Engine



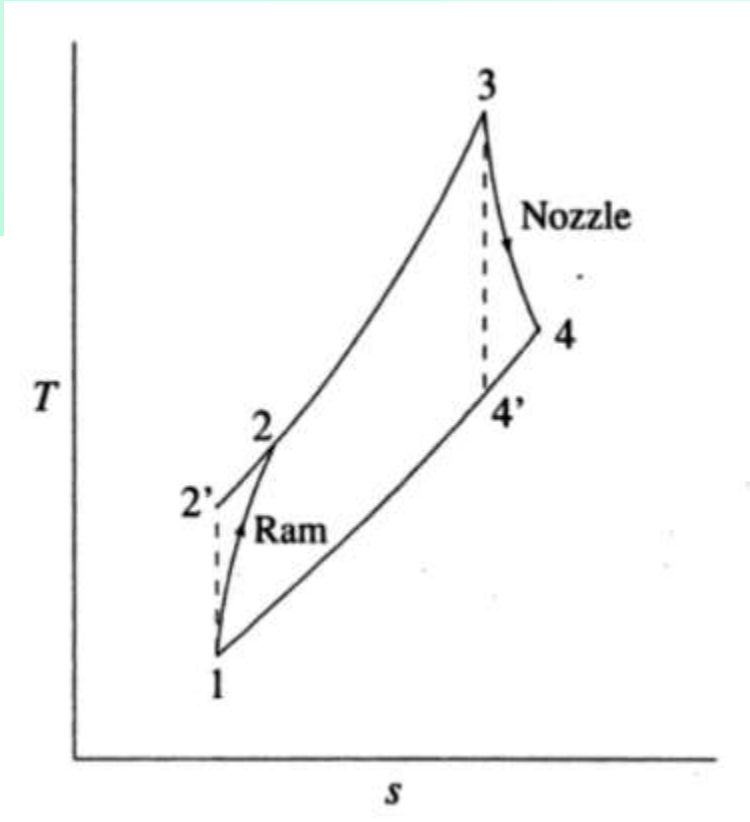
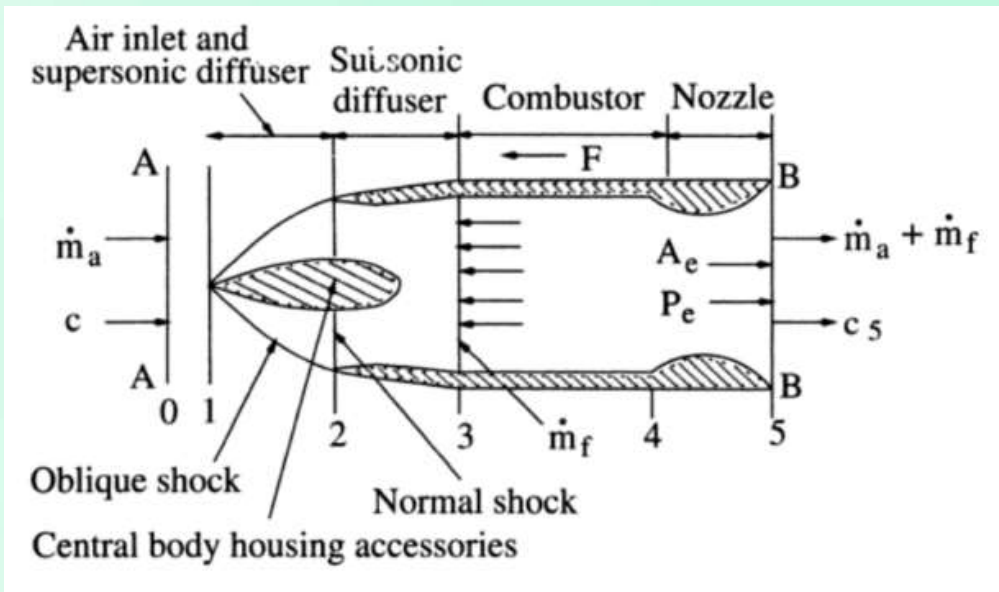
1. Supersonic diffuser (1-2)
2. Subsonic diffuser section (2-3)
3. Combustion chamber (3-4)
4. Discharge nozzle section (4-5)



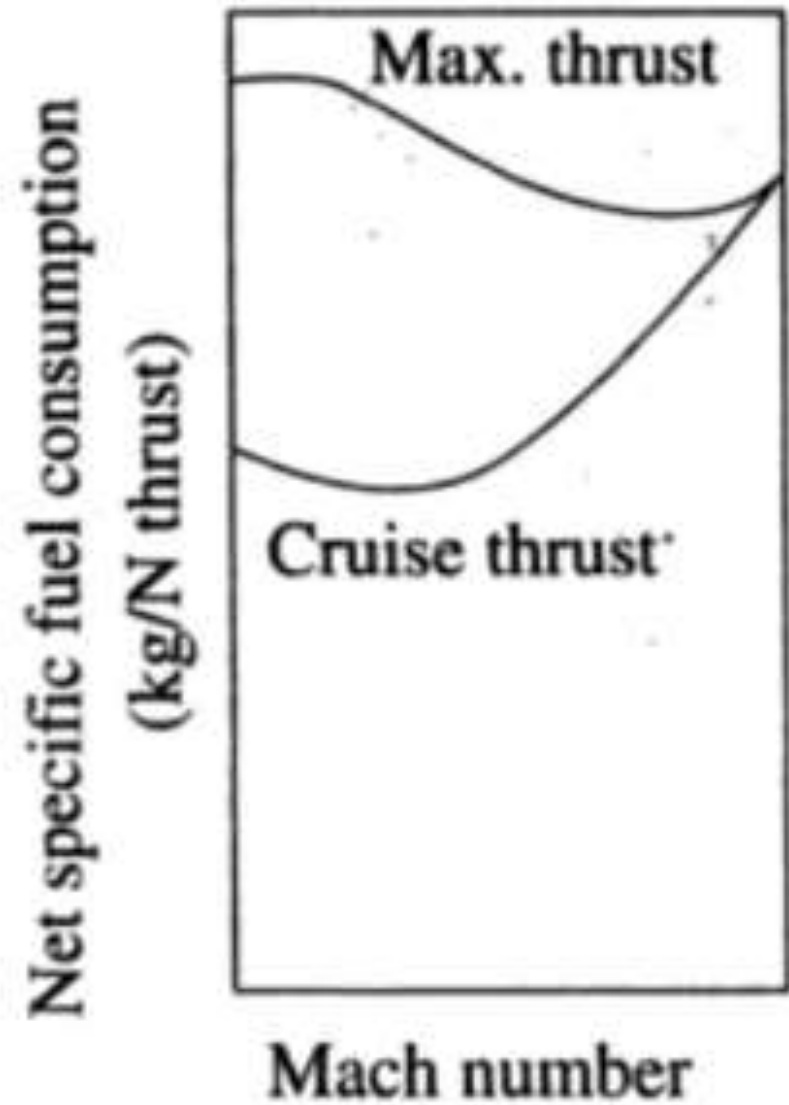
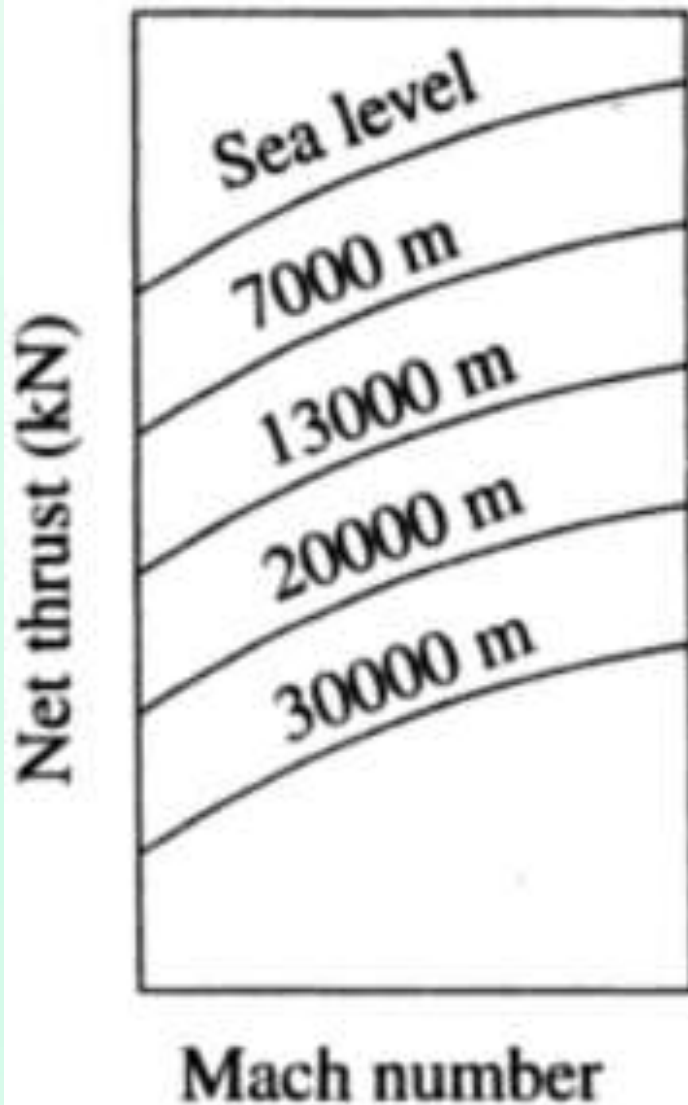
Ramjet Engine



1. Supersonic diffuser (1-2)
2. Subsonic diffuser section (2-3)
3. Combustion chamber (3-4)
4. Discharge nozzle section (4-5)



Ramjet Engine - Performance





Advantages

1. No moving parts, no maintenance
2. No turbine, $T_{max} = 2000^{\circ}\text{C}$
3. Greater thrust with $1/f = 13:1$
4. *SFC* is better than other gas turbine power plants at high speed and high altitudes
5. Theoretically no upper limit on the flight speed



Disadvantages

1. Take-off thrust is zero. Needs external launching device
2. Engine relies on diffuser and designing one with good pressure recovery over a wide range of speeds is very difficult
3. High air speed, CC requires flame holder
4. At very high T dissociation of products of combustion occurs reducing η of the plant if not required during expansion



1. Simple engine and easy for mass production, cheap
2. Even solid fuels can be used
3. Fuel consumption is very large for aircraft propulsion or in missiles at low and moderate speeds
4. Fuel consumption decreases with flight speed and approaches a reasonable value at $2 < M < 5$
5. Suitable for propelling supersonic missiles
6. Widely used in high-speed military aircrafts and missiles

Pulse Jet Engine



Pulse jet was the power plant of German V-1 bomb popularly known as 'Buzz Bomb' first used in World War II in 1944

