Applied Thermodynamics - II

Gas Turbines – Shaft Power Ideal Cycles

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Introduction

- 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 = $f(r, T_{max})$

Ideal Cycles: Assumptions

The air-standard Brayton cycle

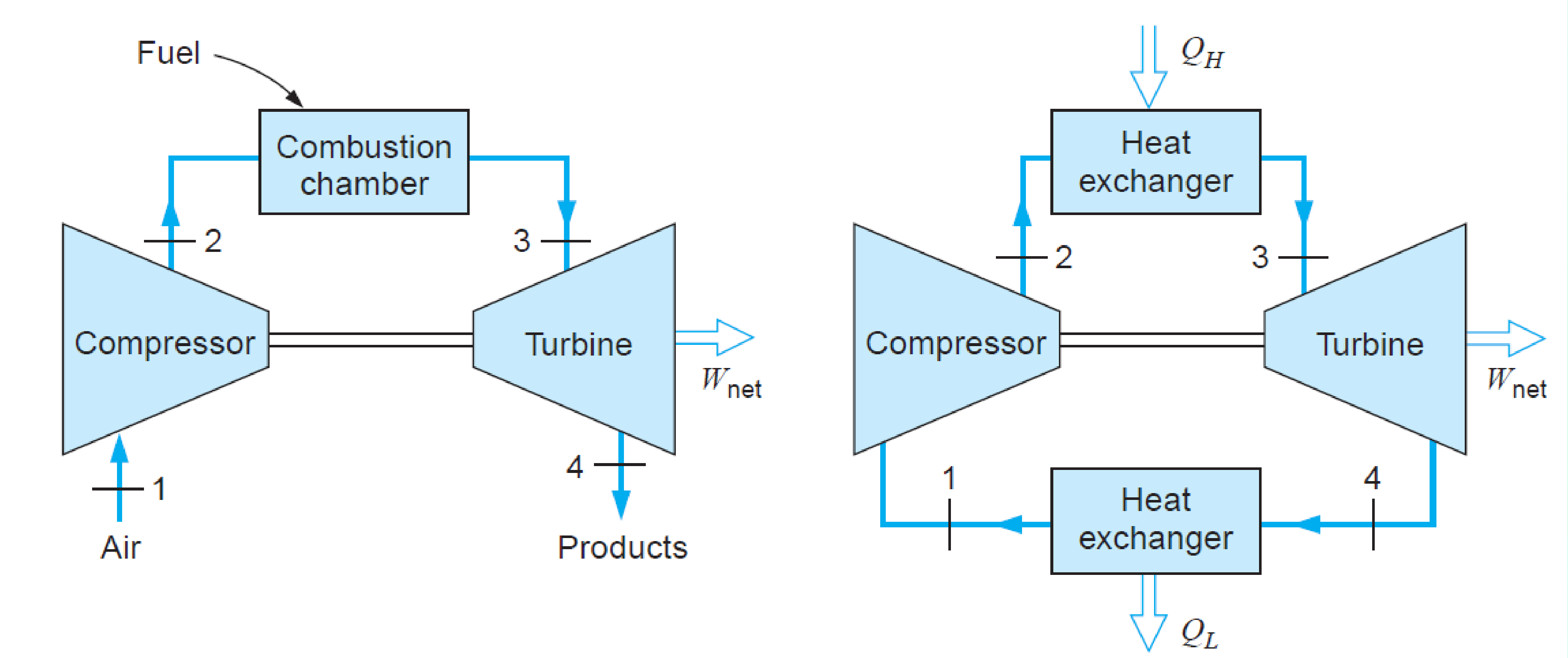
- Compression and expansion processes are reversible and adiabatic, i.e., isentropic
- Negligible change in kinetic energy of the working fluid between inlet and outlet of each component
- No pressure loss
- Working fluid has the same composition throughout the cycle

  What does it mean?

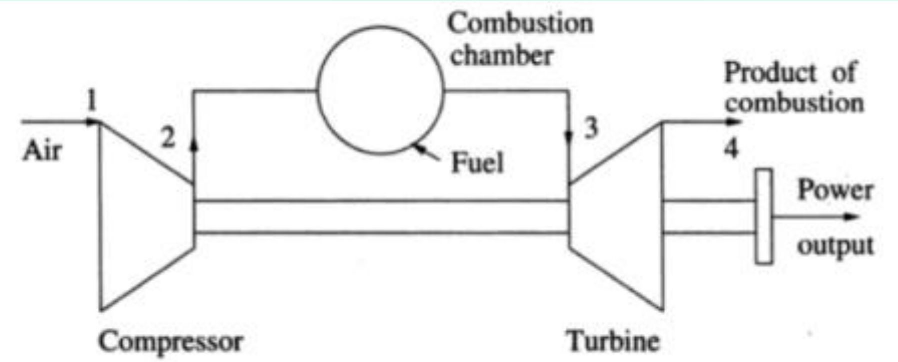
  Ideal cycle: open or closed (doesn’t make any difference)
- Working fluid is a perfect gas with constant specific heats
- Mass flow rate is constant
- Heat transfer in a heat-exchanger is complete

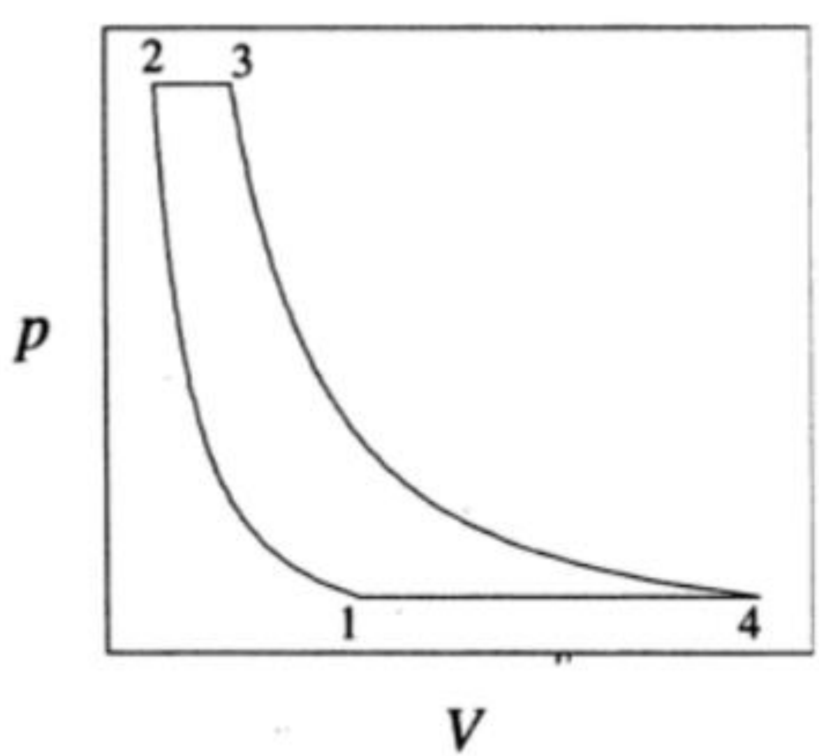
  Temperature rise on cold side = temperature drop on hot side

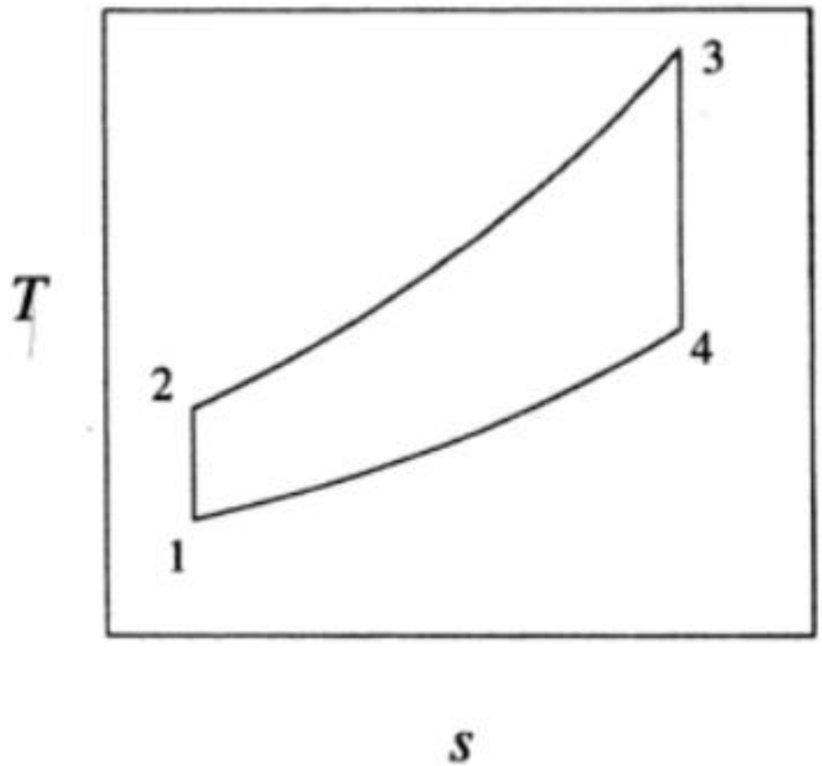
Gas Turbine: Open or Closed Cycle



Brayton (Joule) Cycle







Simple Gas Turbine Cycle Calculations

$$Q = (h_2 - h_1) + \frac{1}{2}(C_2^2 - C_1^2) + W$$

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

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

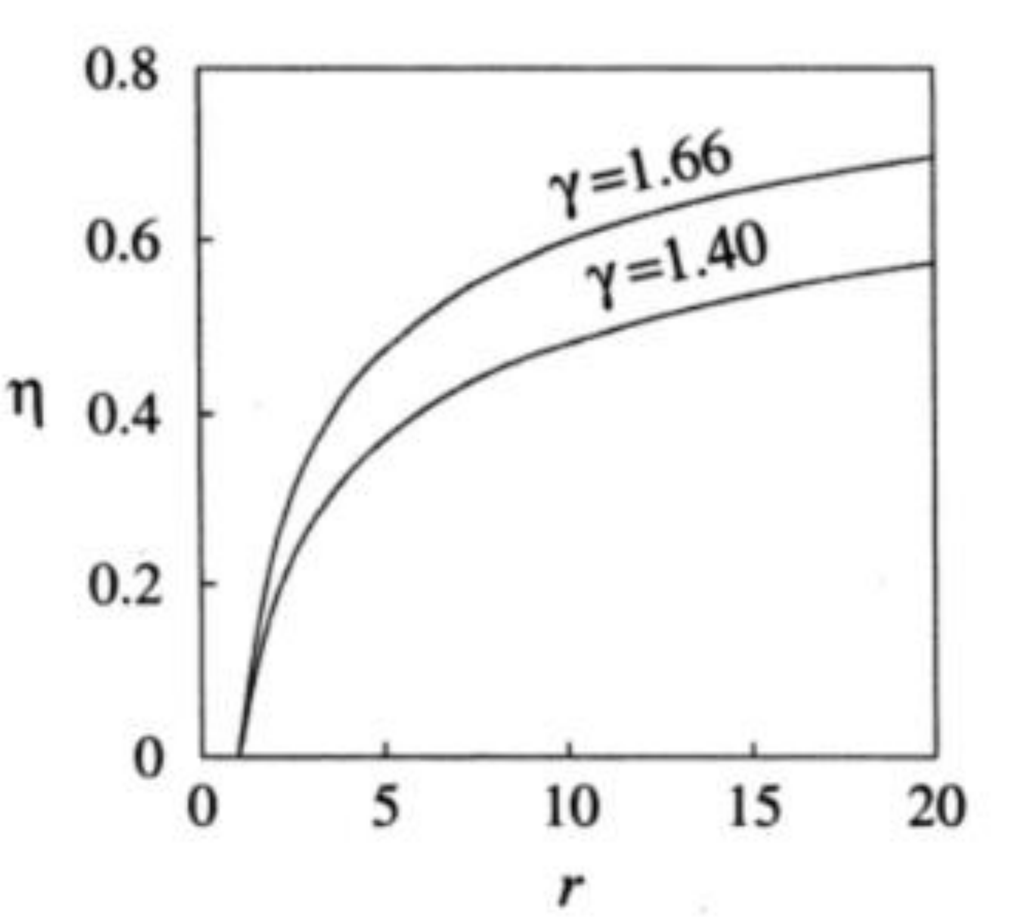
$$\frac{T_2}{T_1} = r^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4} \text{ where } r = \frac{p_2}{p_1} = \frac{p_3}{p_4}$$

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

Simple Gas Turbine Cycle : Efficiency

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

However, this theoretical advantage may not be realized in reality



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

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

Simple Gas Turbine Cycle : Specific Work Output

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

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

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

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

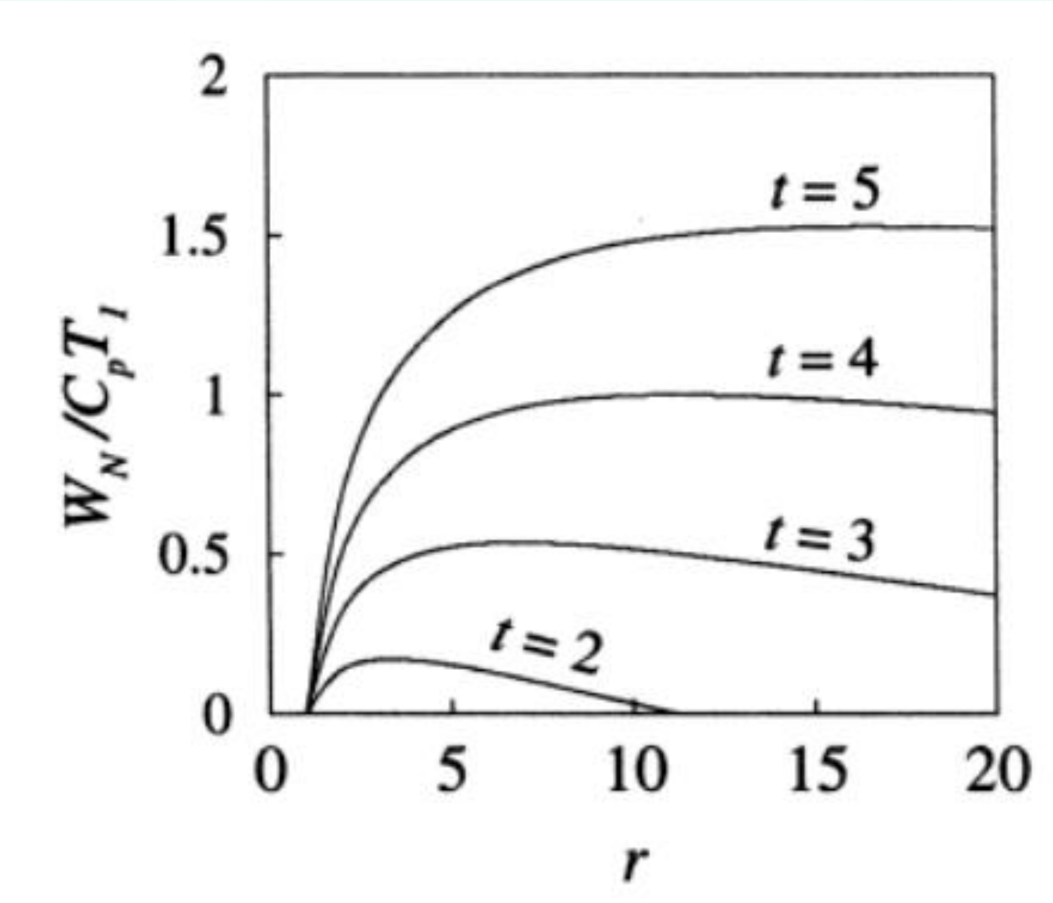
$$t = c^2$$

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

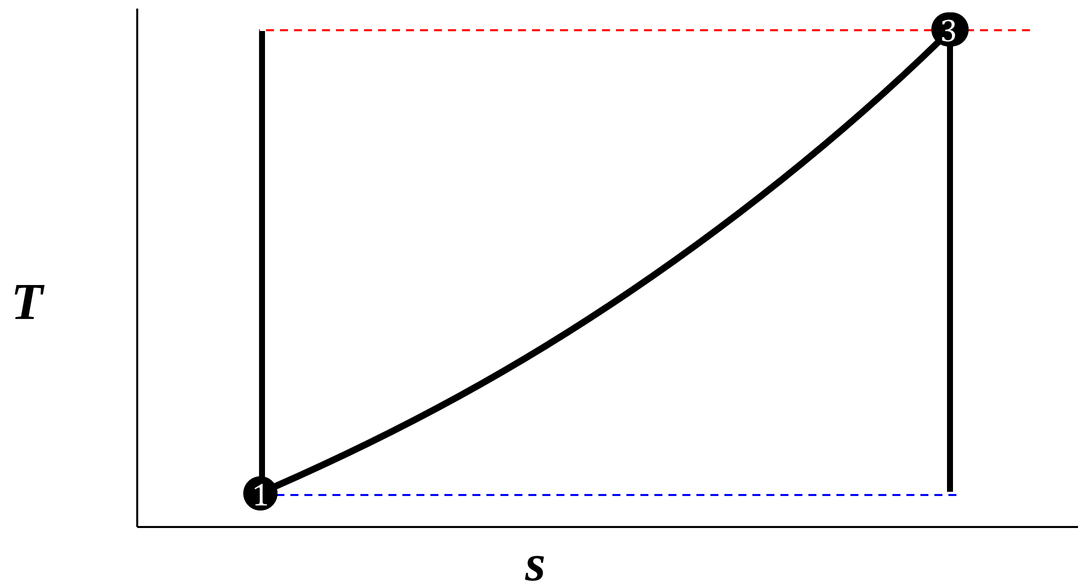
Specific work output is maximum at $T_2 = T_4$

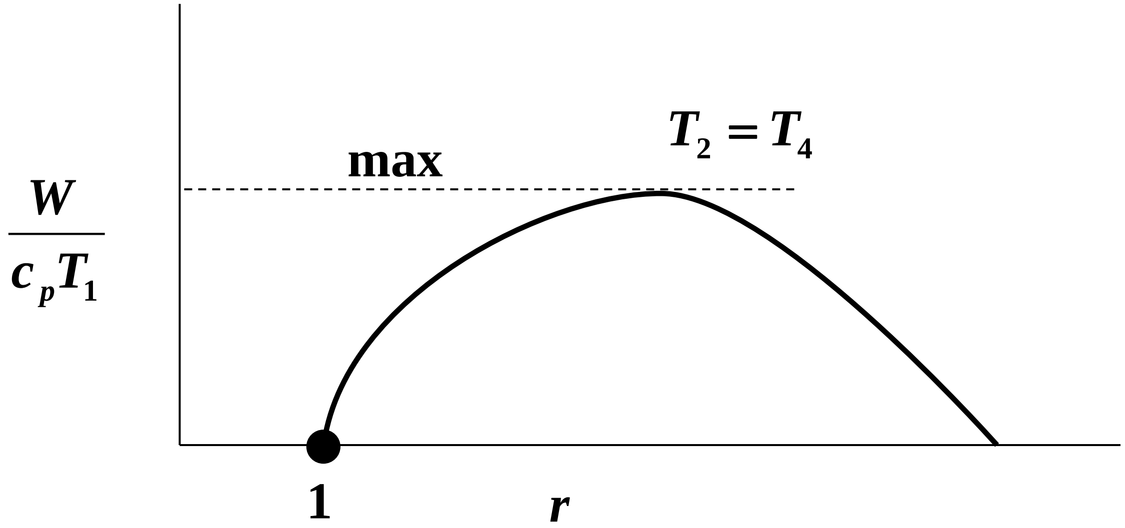
Simple Gas Turbine Cycle : Specific Work Output

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

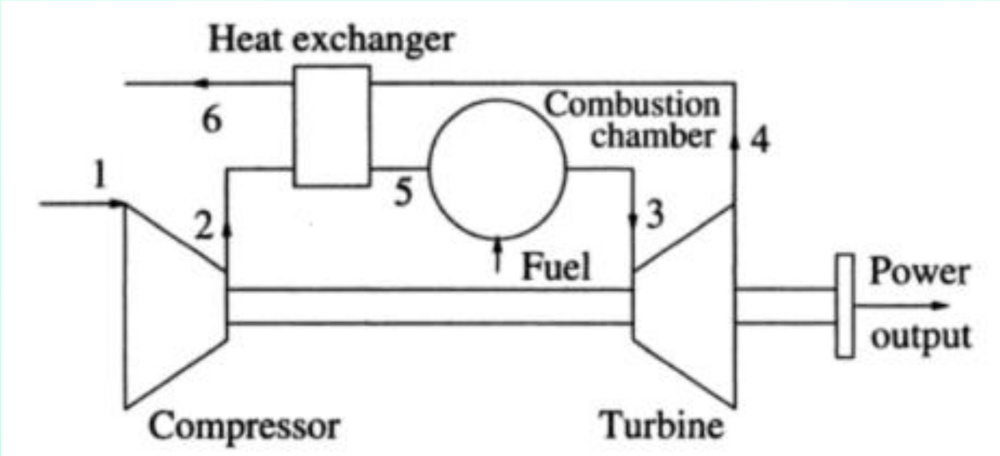


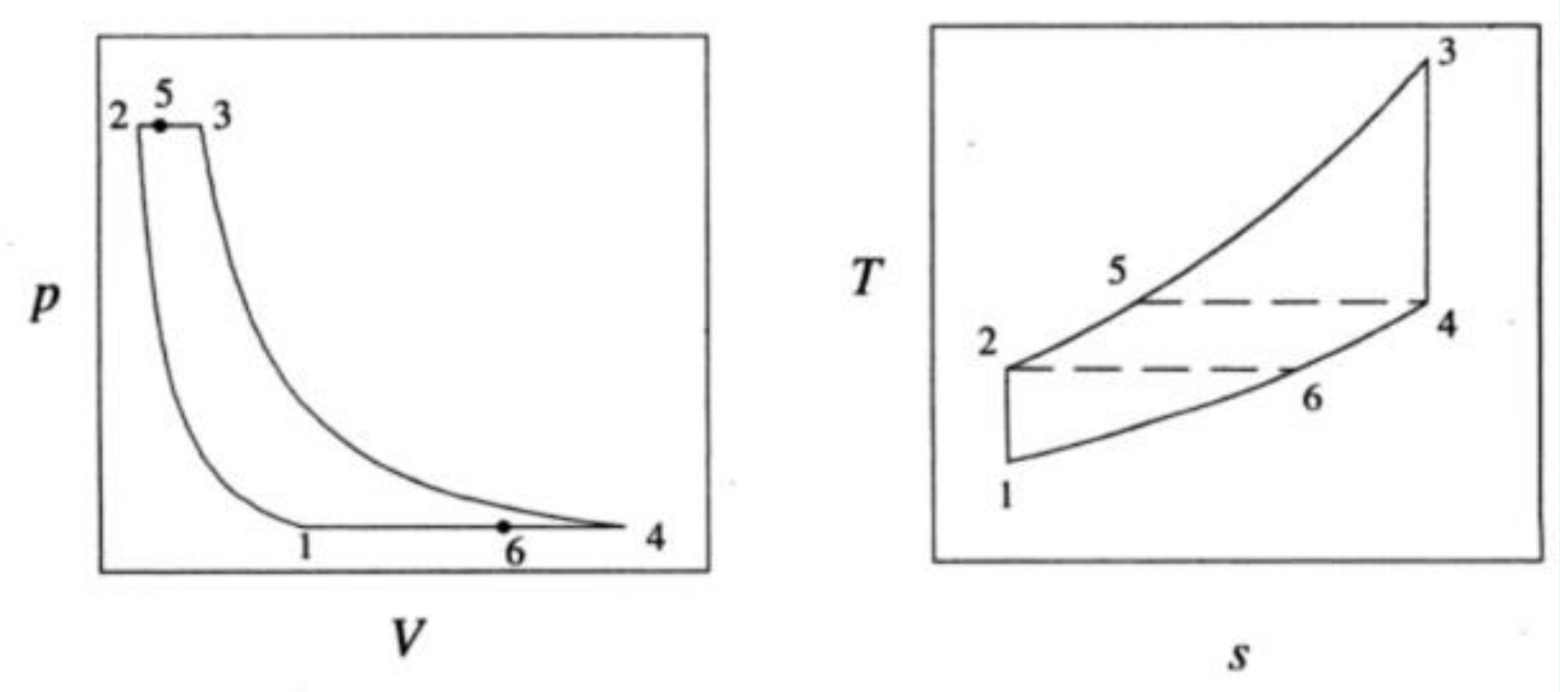
Simple Gas Turbine Cycle : Specific Work Output





Heat Exchanger Cycle





Heat Exchanger Cycle: Efficiency

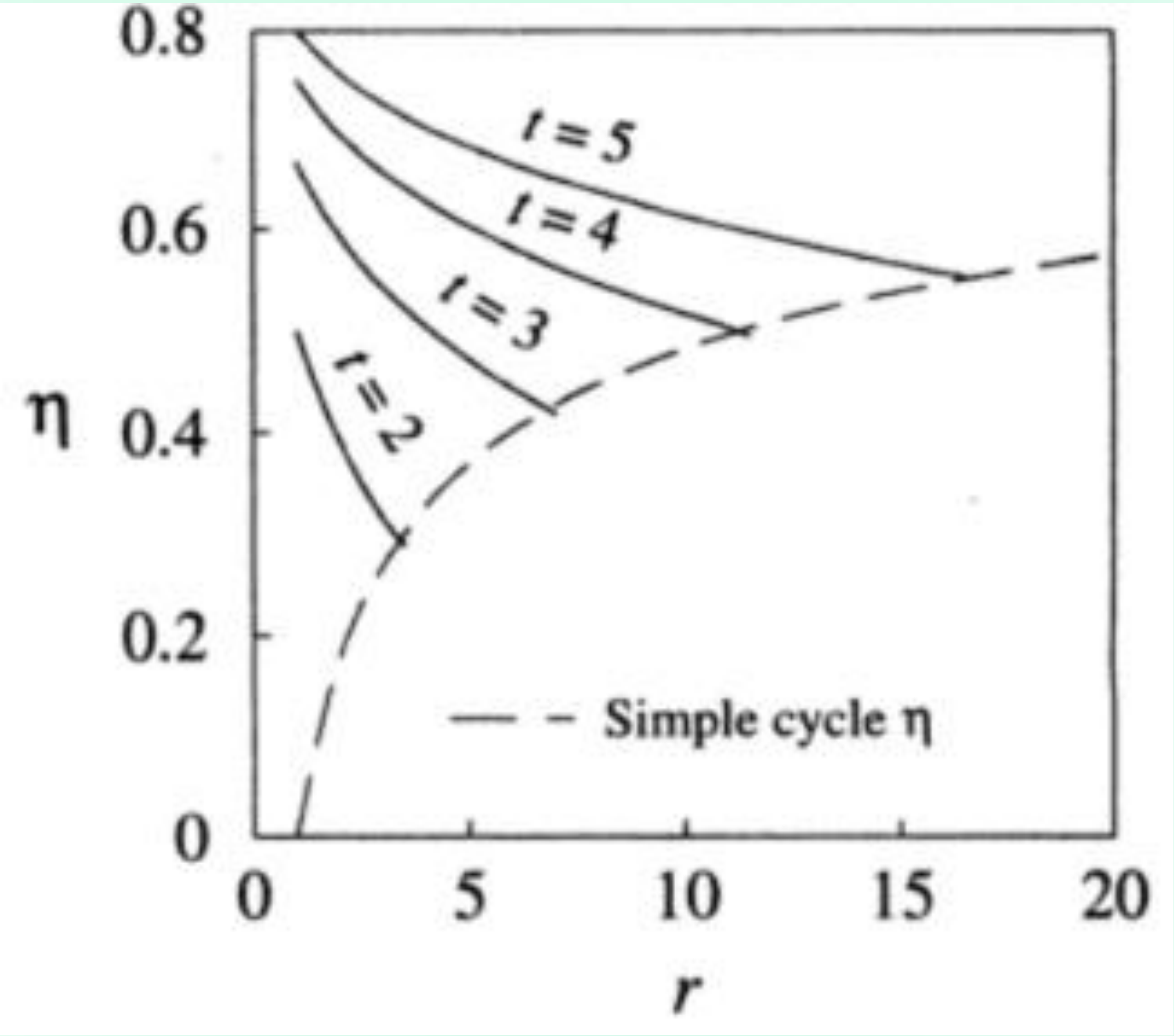
$$\boldsymbol{\eta = 1 - \frac{c}{t}}$$

- 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

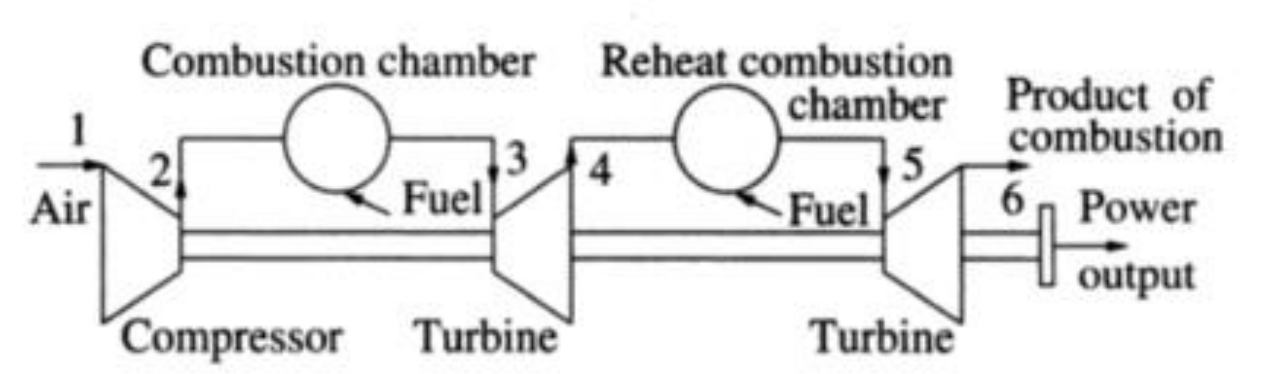
$$\boldsymbol{\frac{W}{c_p T_1} = t\left(1 - \frac{1}{c}\right) - (c - 1)}$$

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

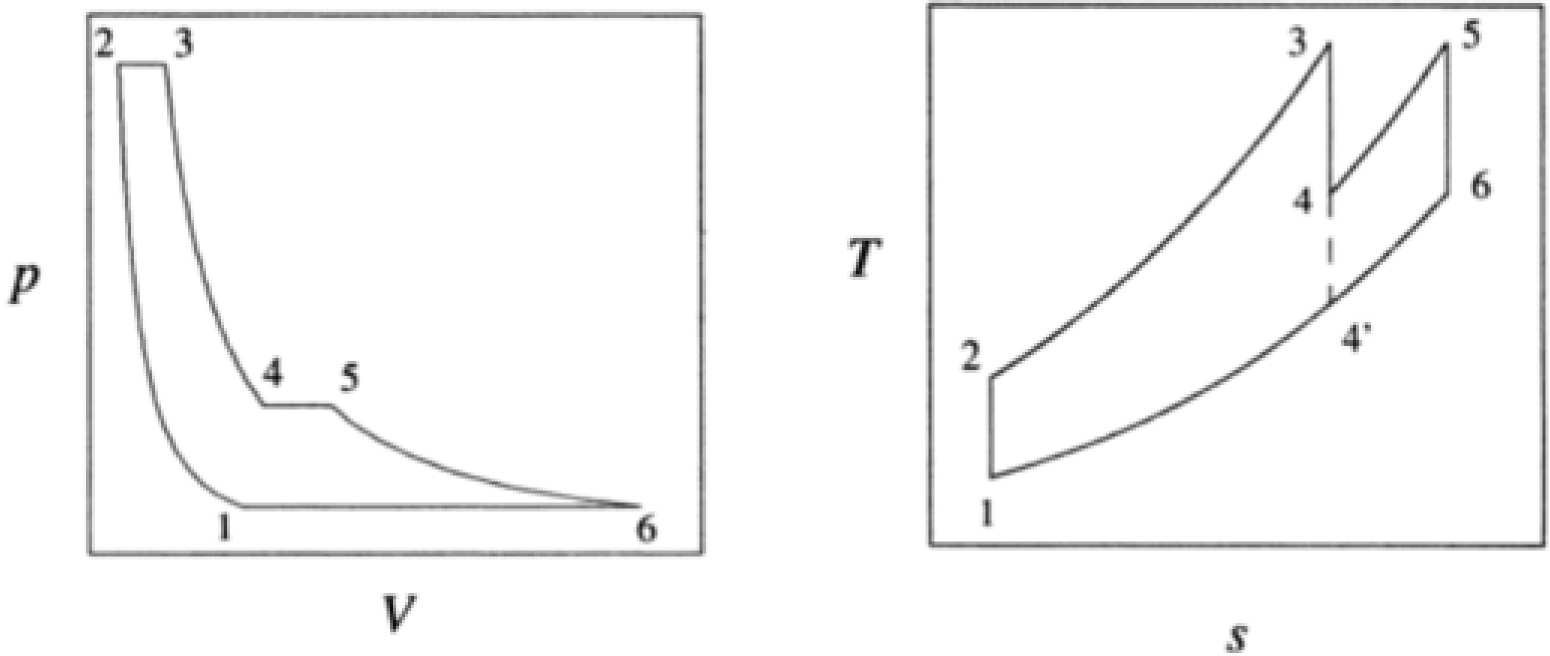
Heat Exchanger Cycle: Efficiency



Reheat Cycle

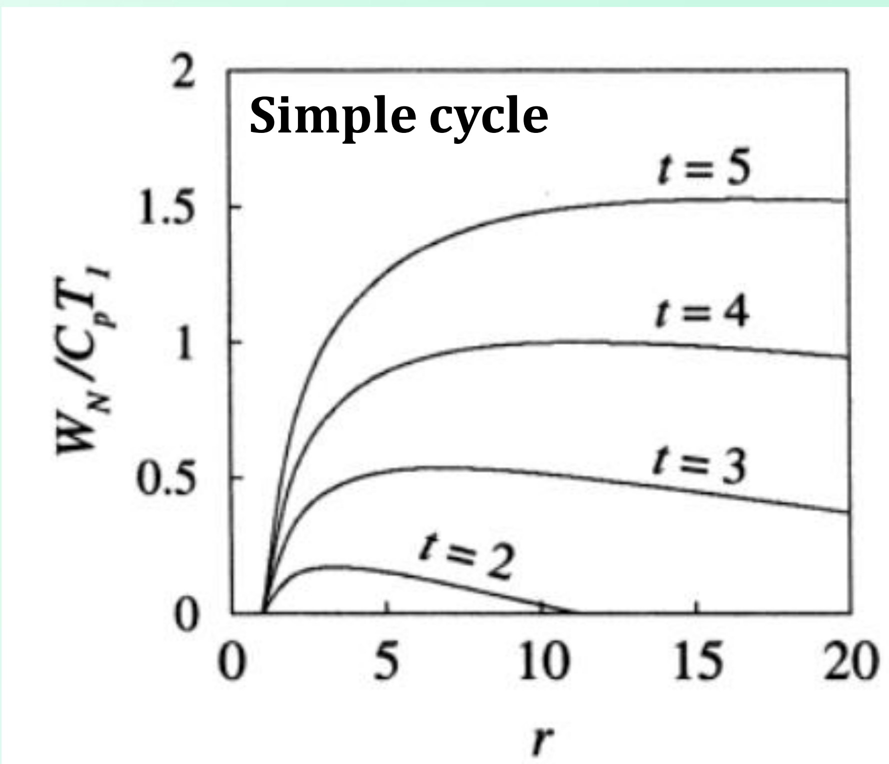


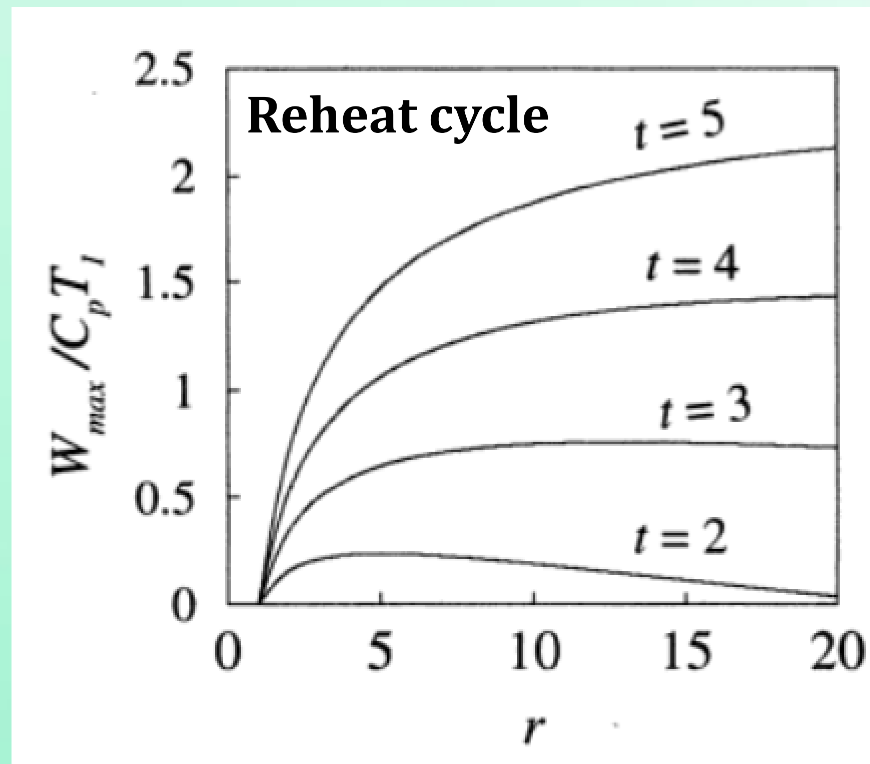
$$(T_3 - T_4) + (T_5 - T_6) > (T_3 - T'_4)$$



Reheat Cycle: Specific Work Output

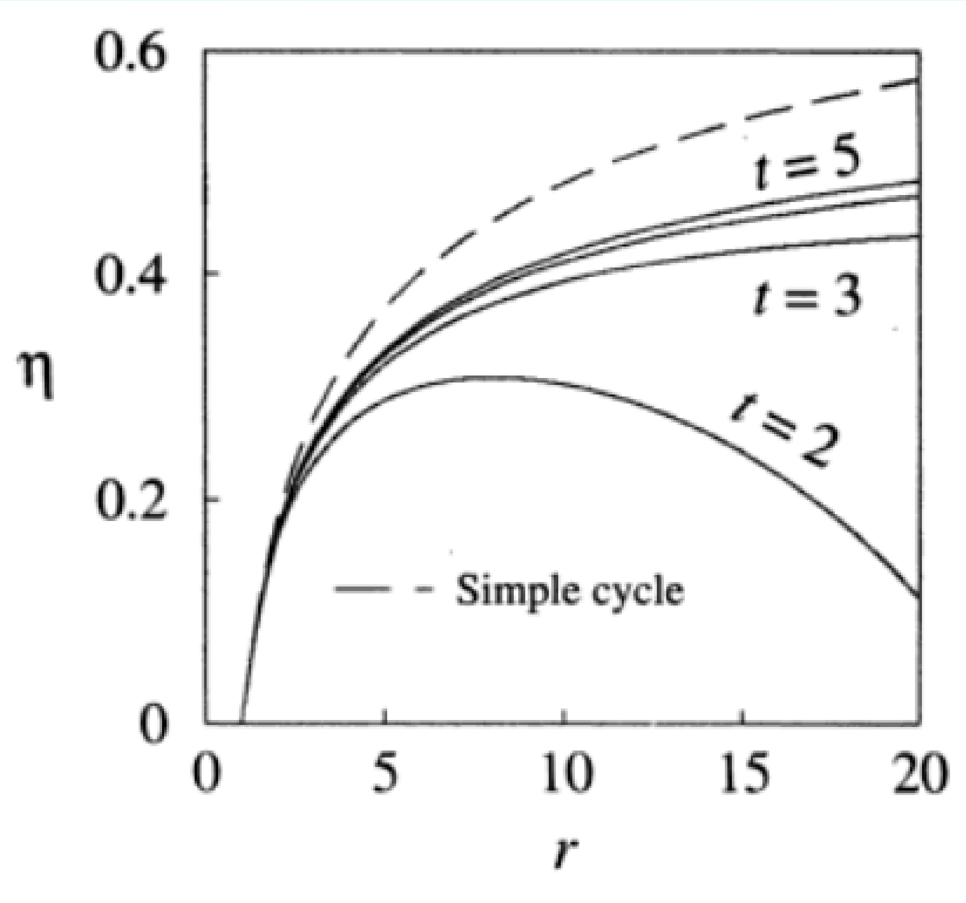
$$\frac{W_{\max}}{c_p T_1} = 2t - c + 1 - \frac{2t}{\sqrt{c}}$$



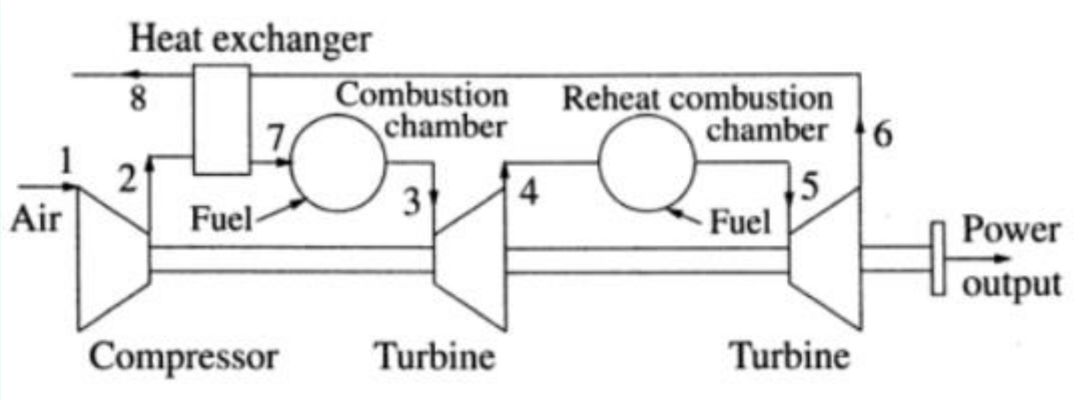


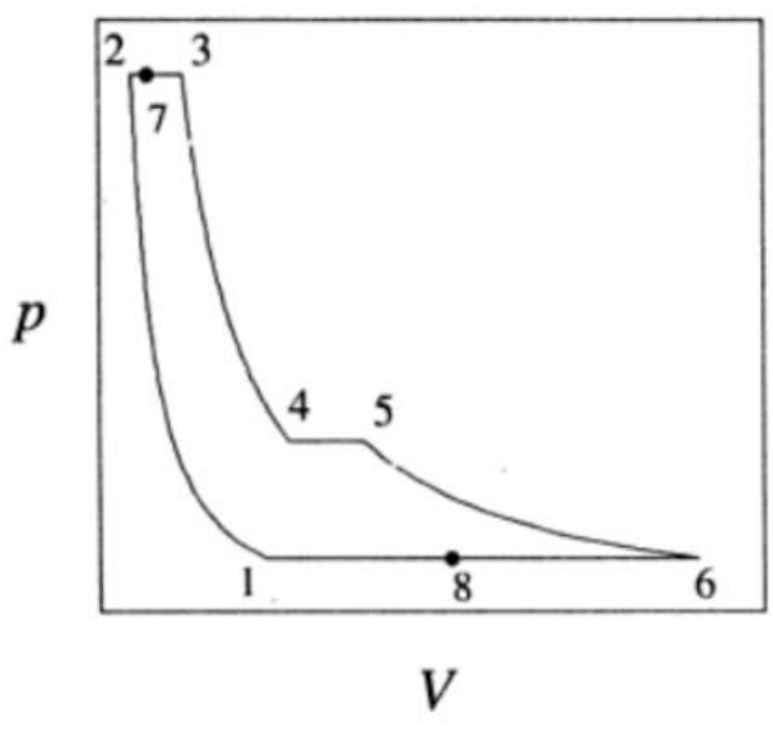
Reheat Cycle: Efficiency

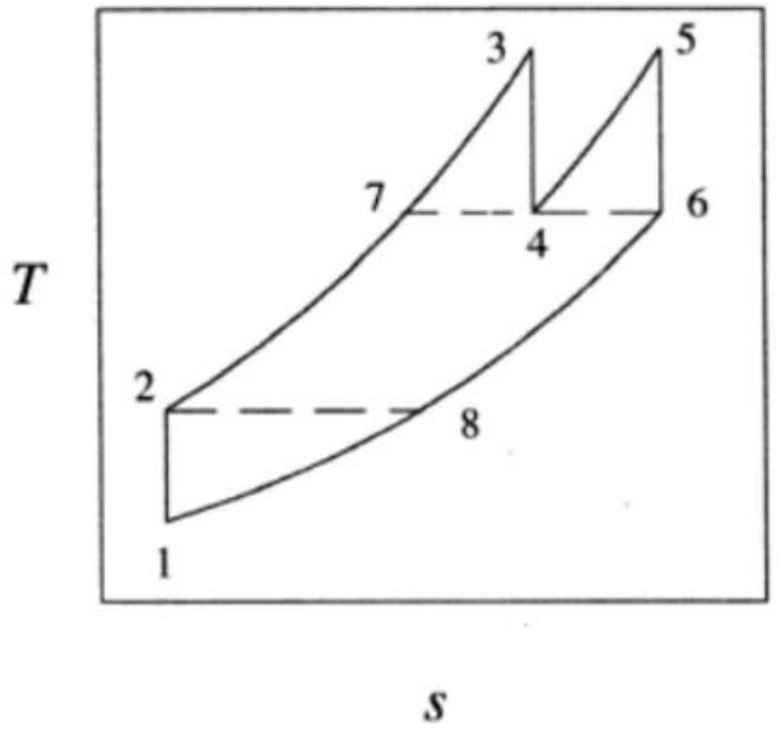
$$\eta_{max} = \frac{2t - c + 1 - 2t/\sqrt{c}}{2t - c - t/\sqrt{c}}$$



Reheat & Heat Exchange Cycle

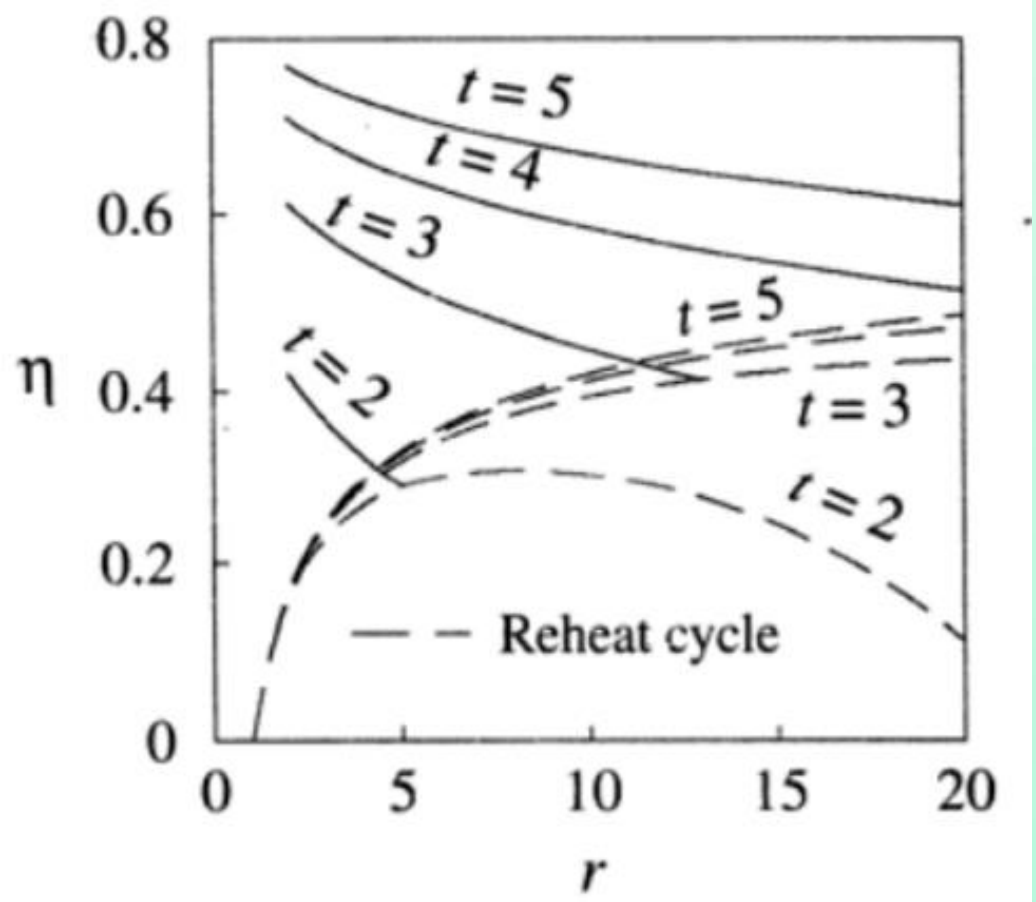




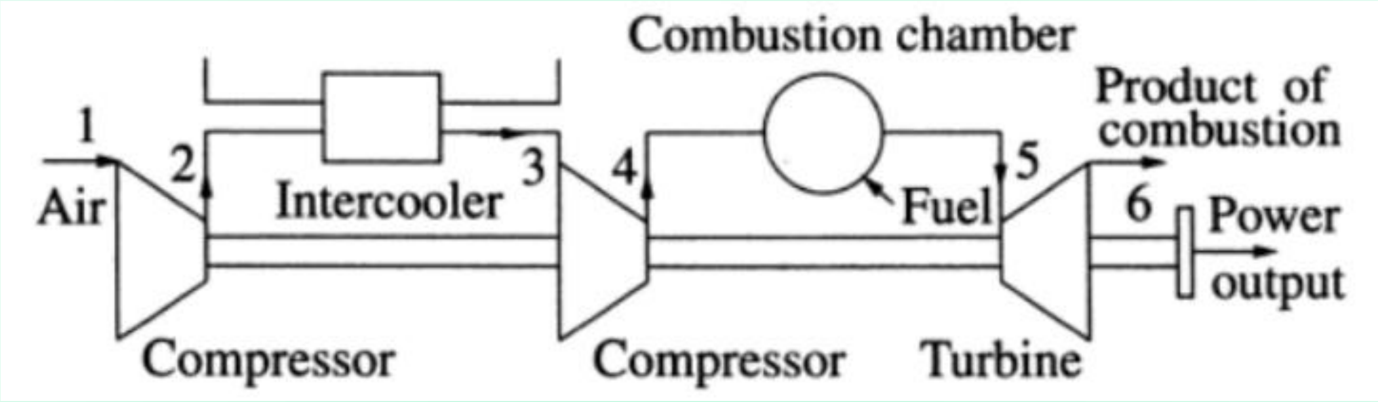


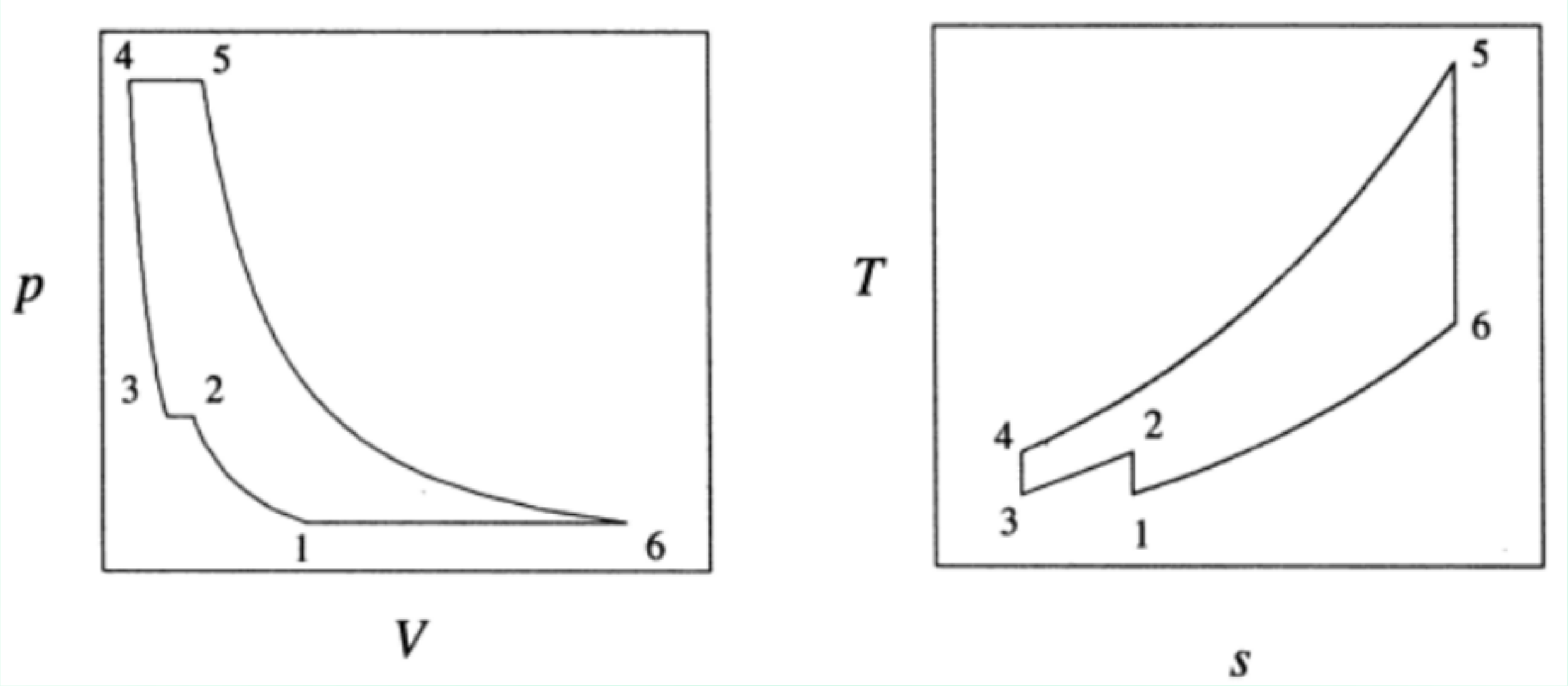
Reheat & Heat Exchange Cycle: Efficiency

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



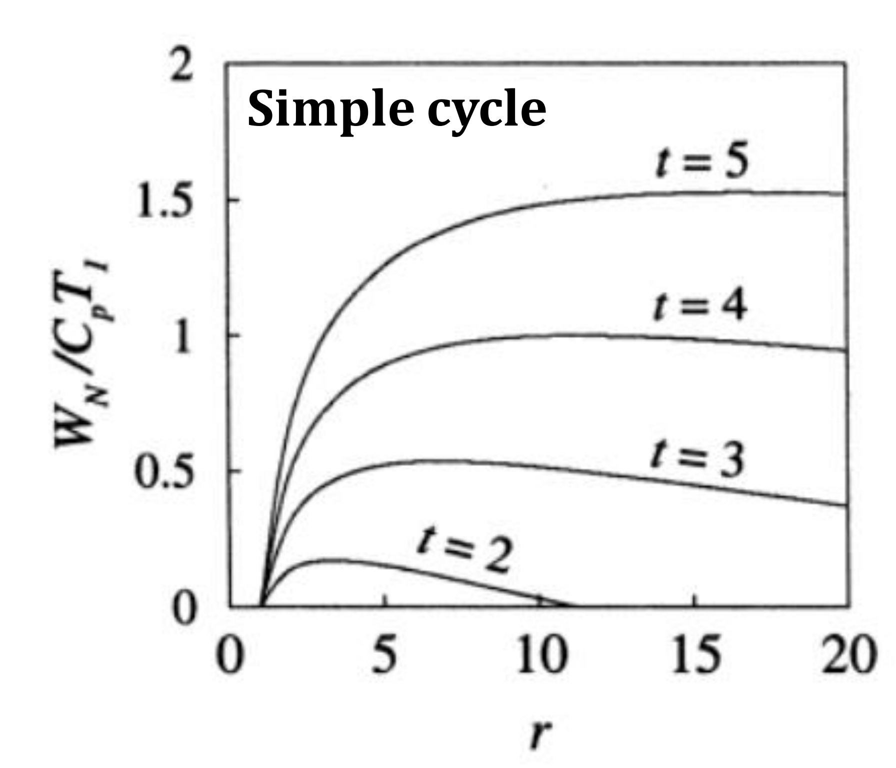
Intercooled Cycle

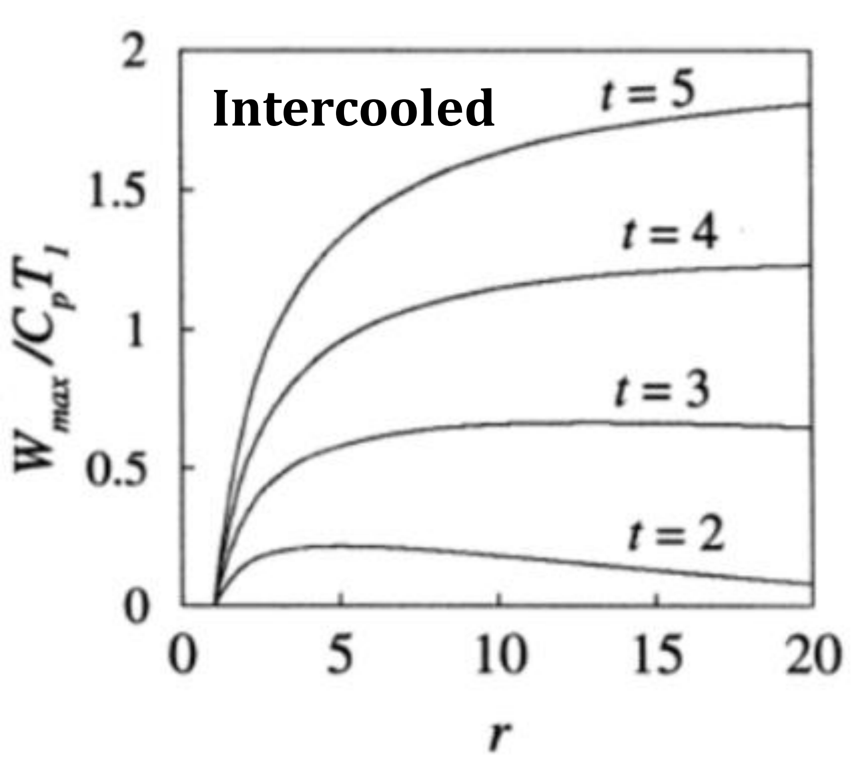




Intercooled Cycle: Specific Work Output

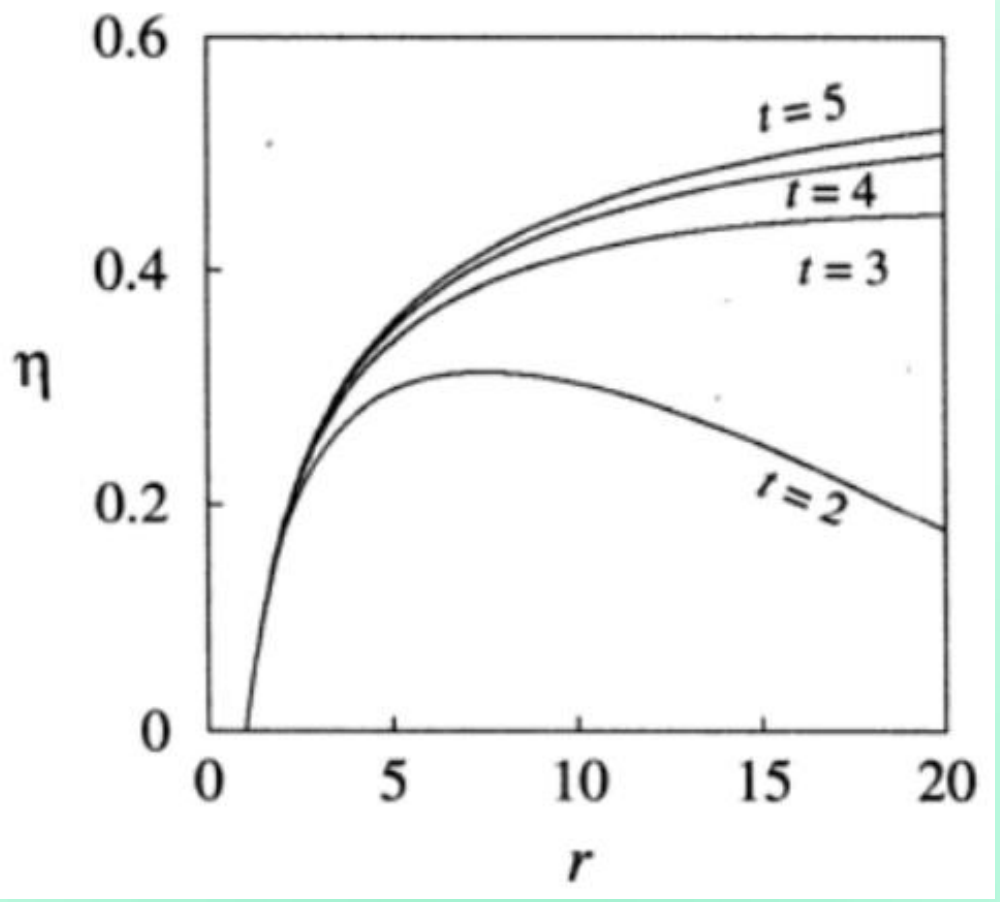
$$\frac{W_{\max}}{c_p T_1} = t - \frac{t}{c} - 2\sqrt{c} + 2$$





Intercooled Cycle: Efficiency

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

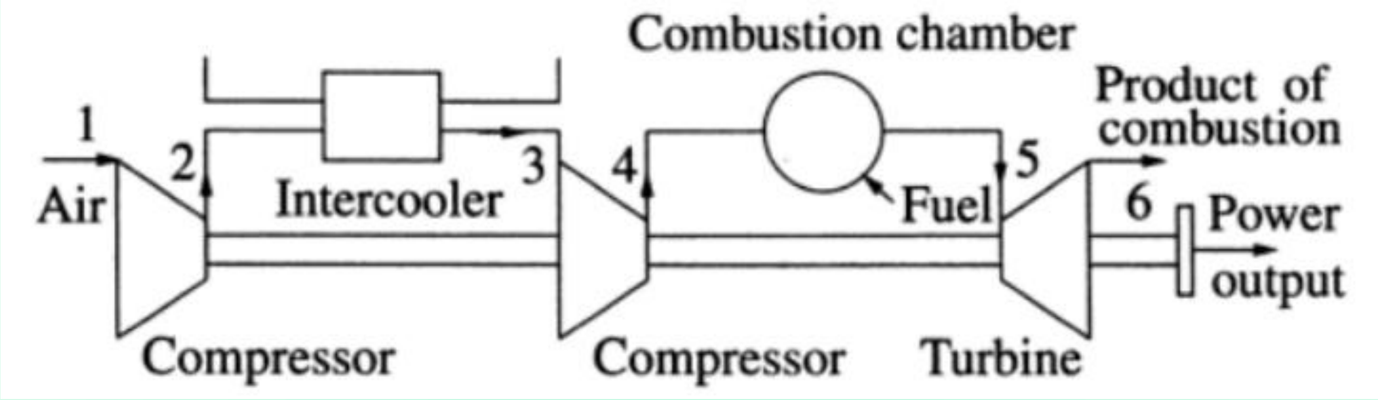


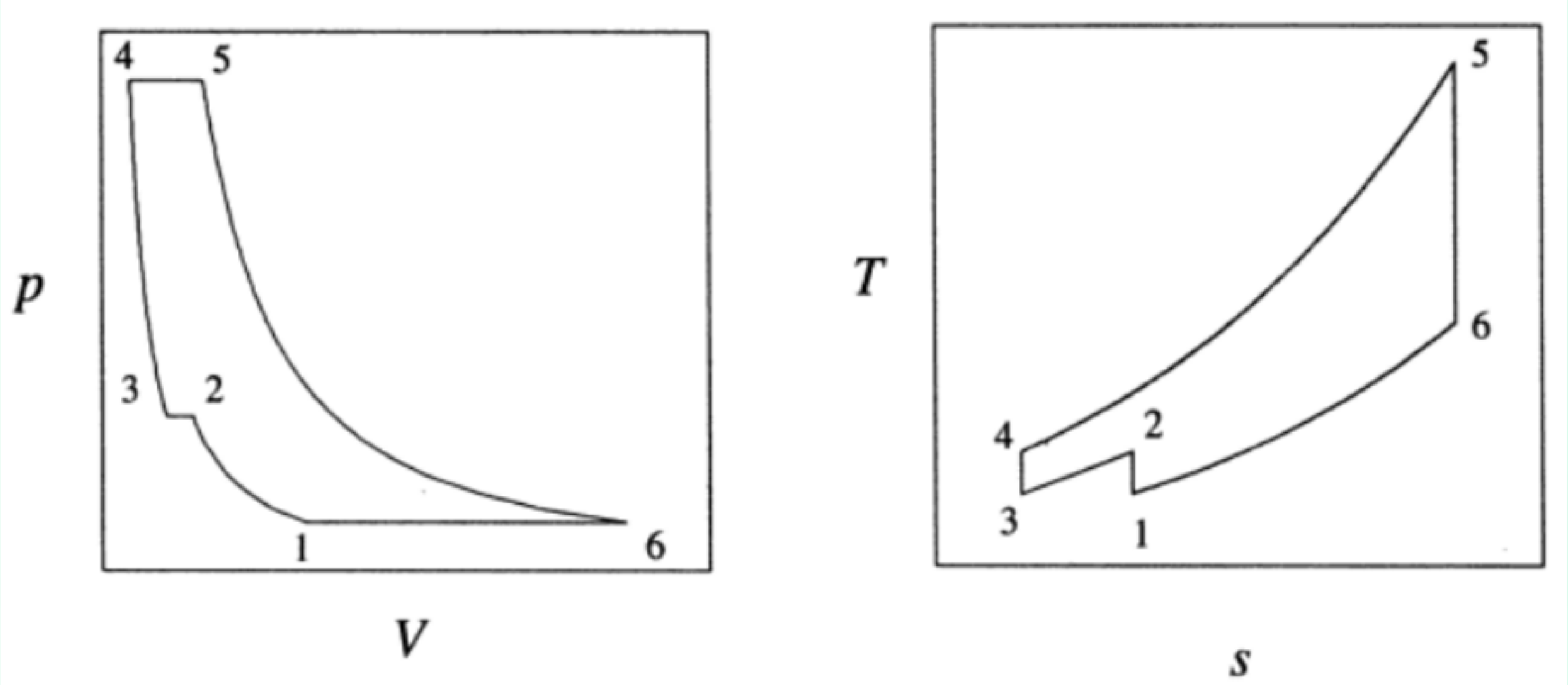
Quiz 02

Derive an expression for maximum specific work output and maximum efficiency of an ideal gas turbine consisting of intercooled cycle with heat exchanger. Plot the maximum efficiency against the compression ratio for $t = 2, 3$. Comment.

Hint: Assumptions, Schematic arrangement, *p*-*V* and *T*-*s* diagram, Maximum specific Work output, Maximum efficiency, η_{max} vs *r*, and Comments.

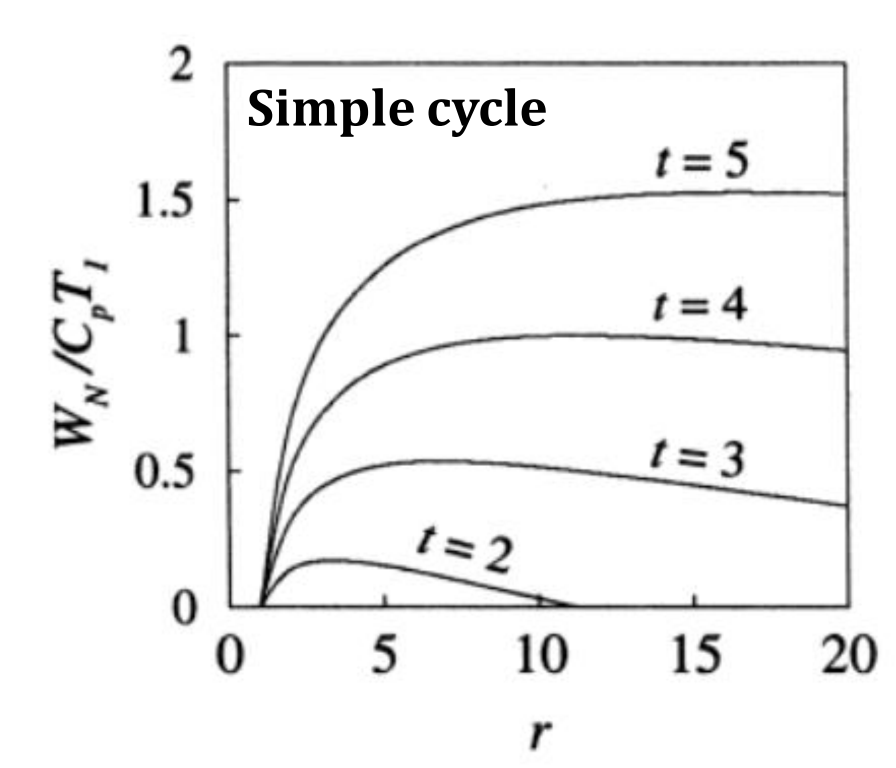
Intercooled Cycle

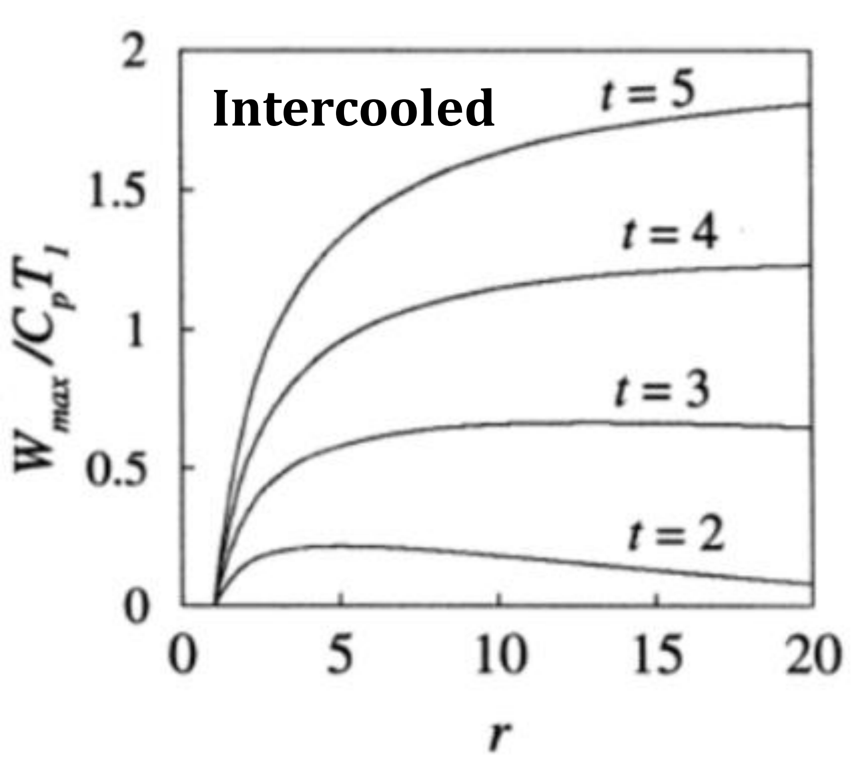




Intercooled Cycle: Specific Work Output

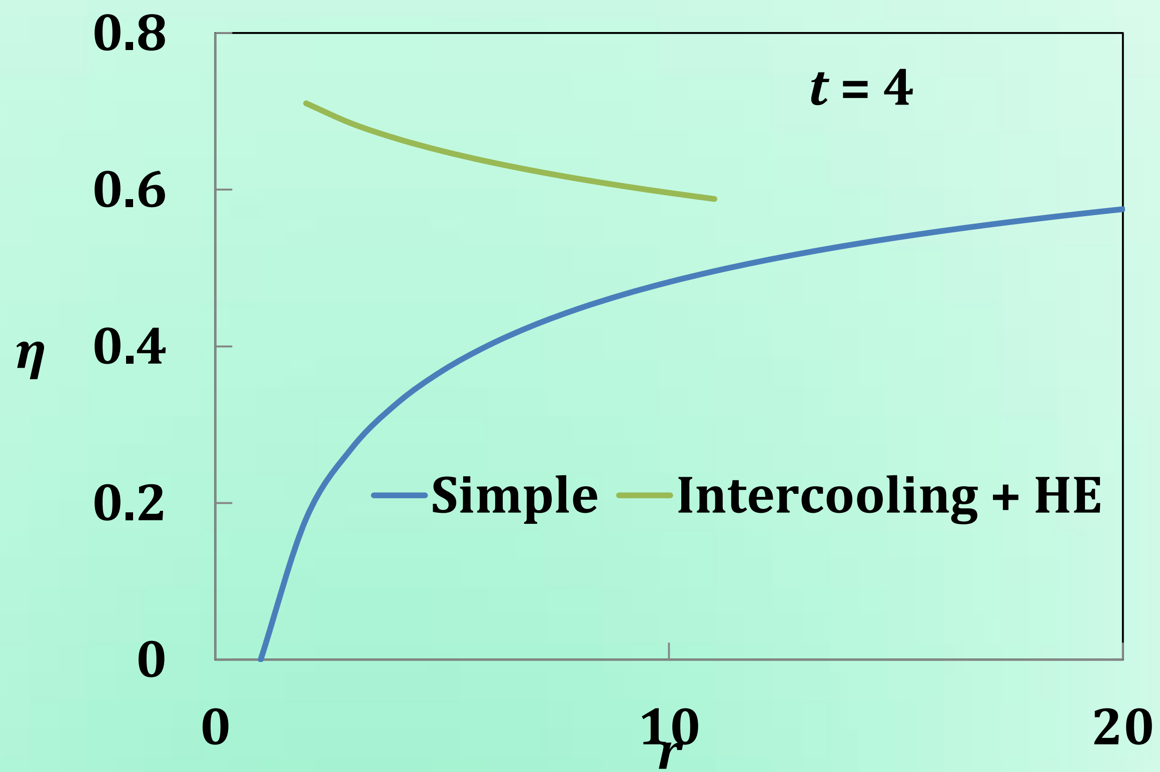
$$\frac{W_{\max}}{c_p T_1} = t - \frac{t}{c} - 2\sqrt{c} + 2$$



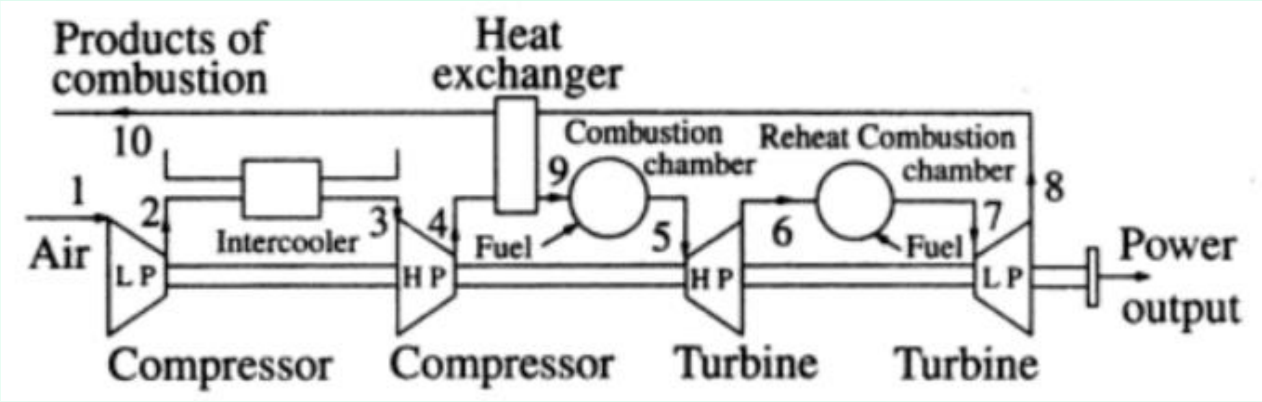


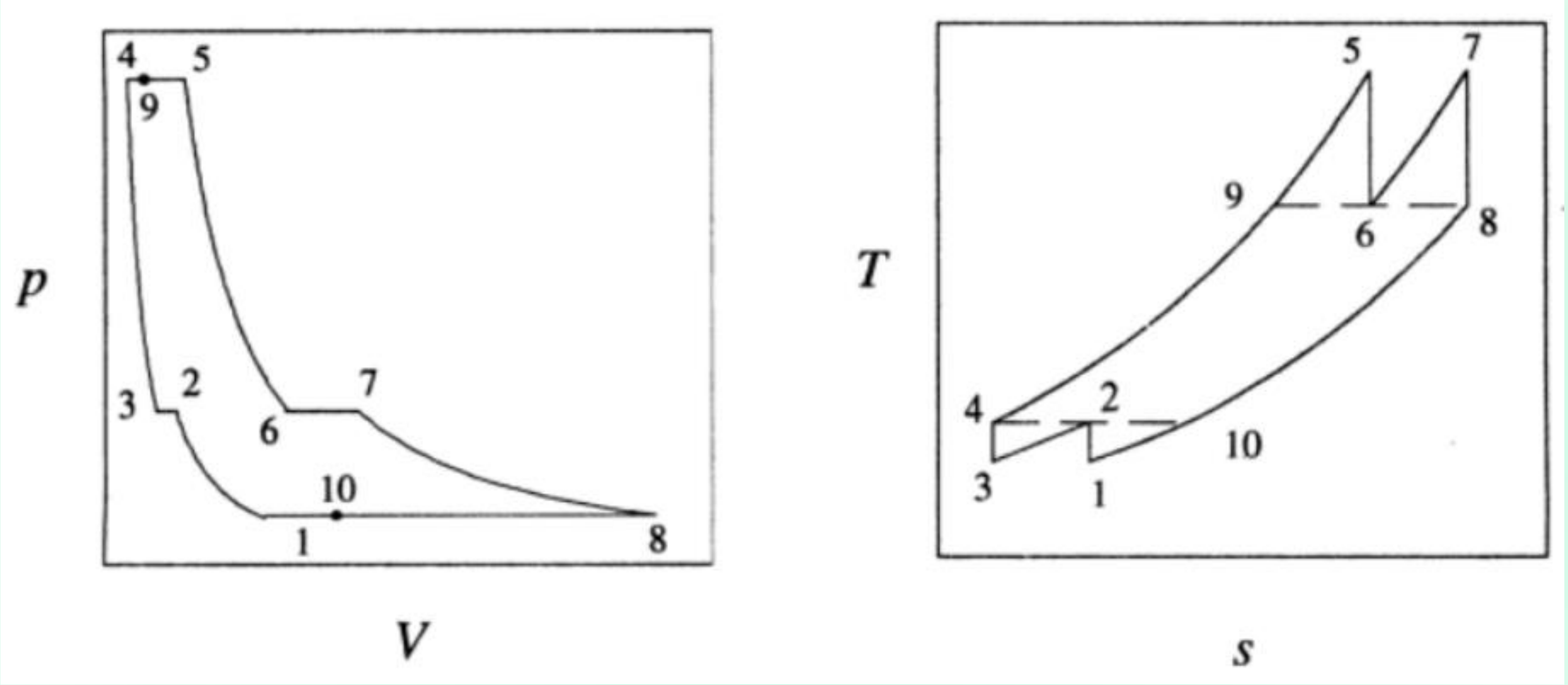
Intercooled with Heat Exchanger Cycle: Efficiency

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



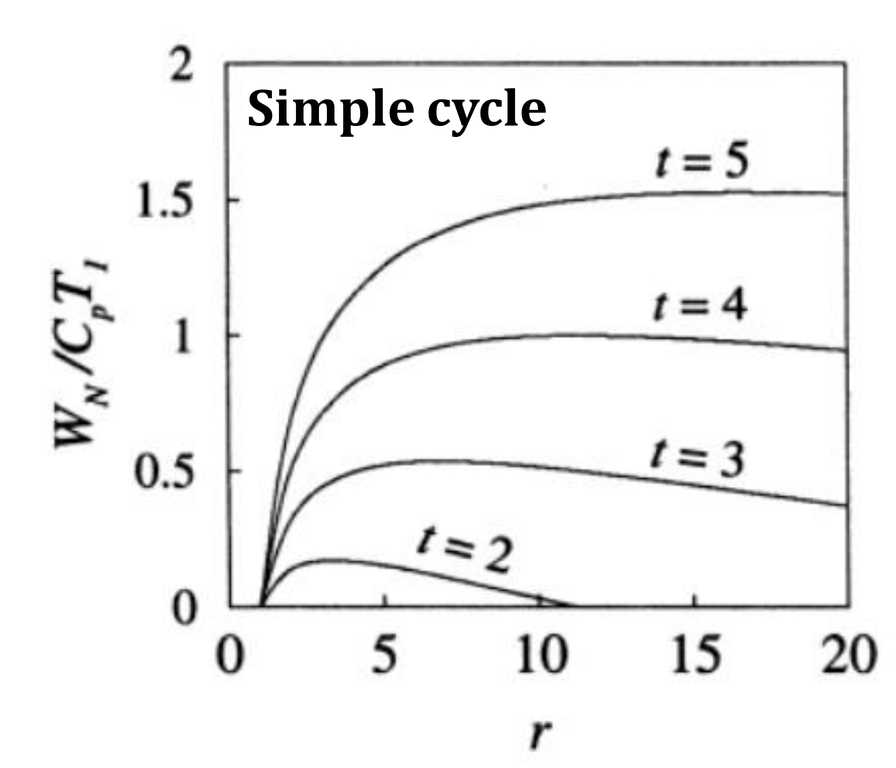
Intercooled, Reheat & Heat Exchange

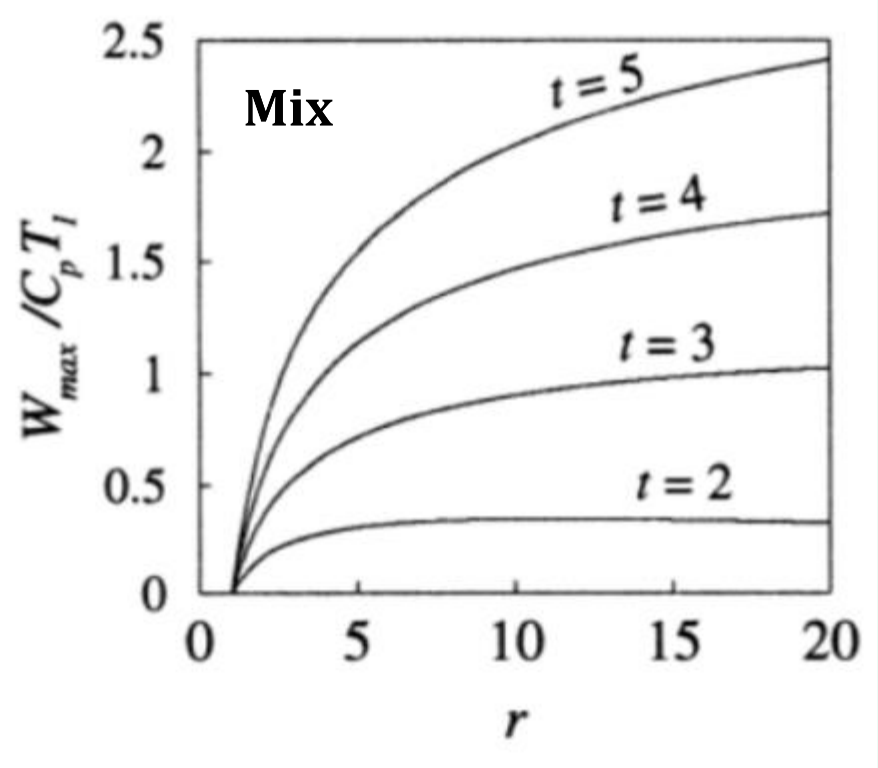




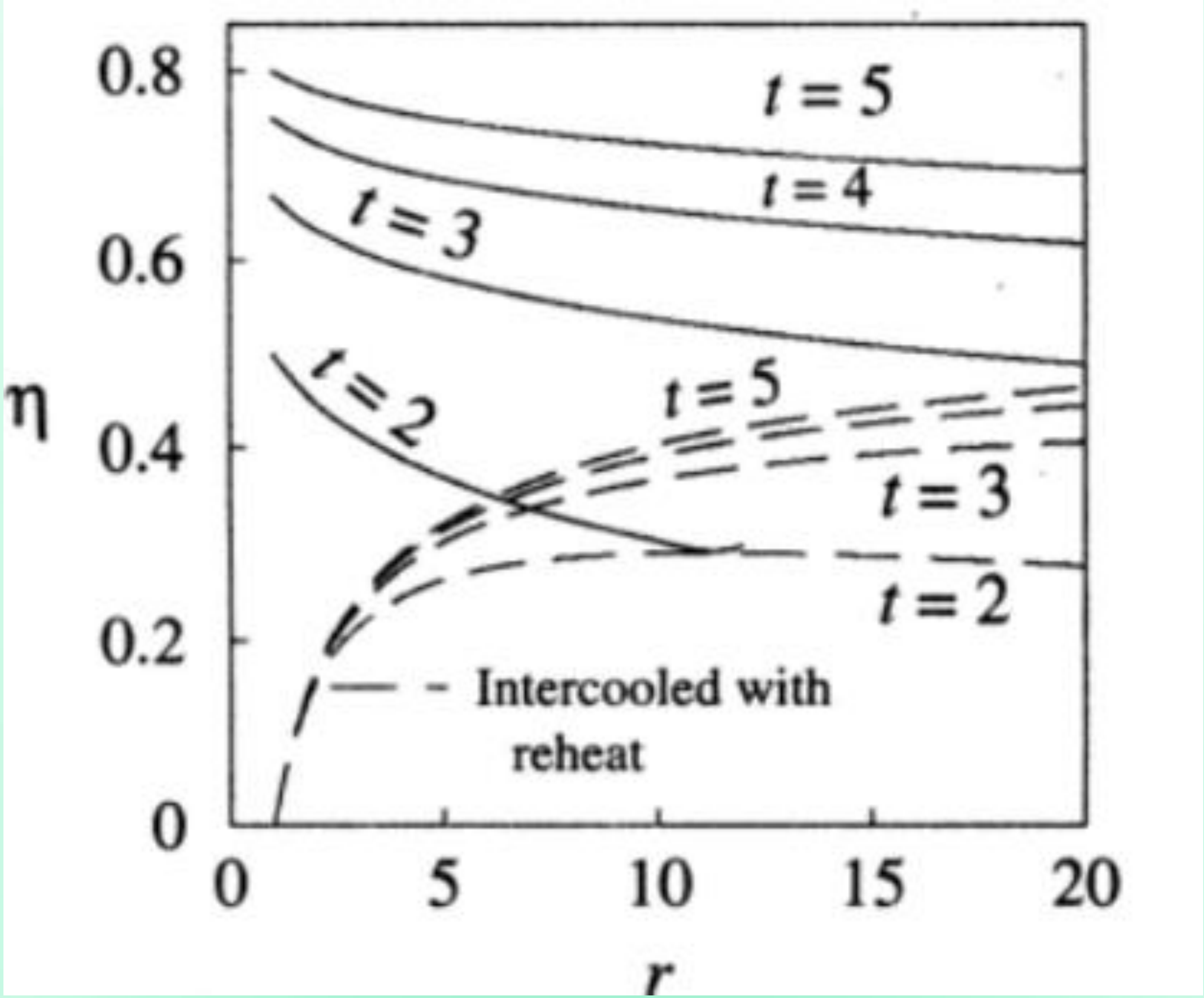
Intercooled, Reheat & Heat Exchange: Work

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

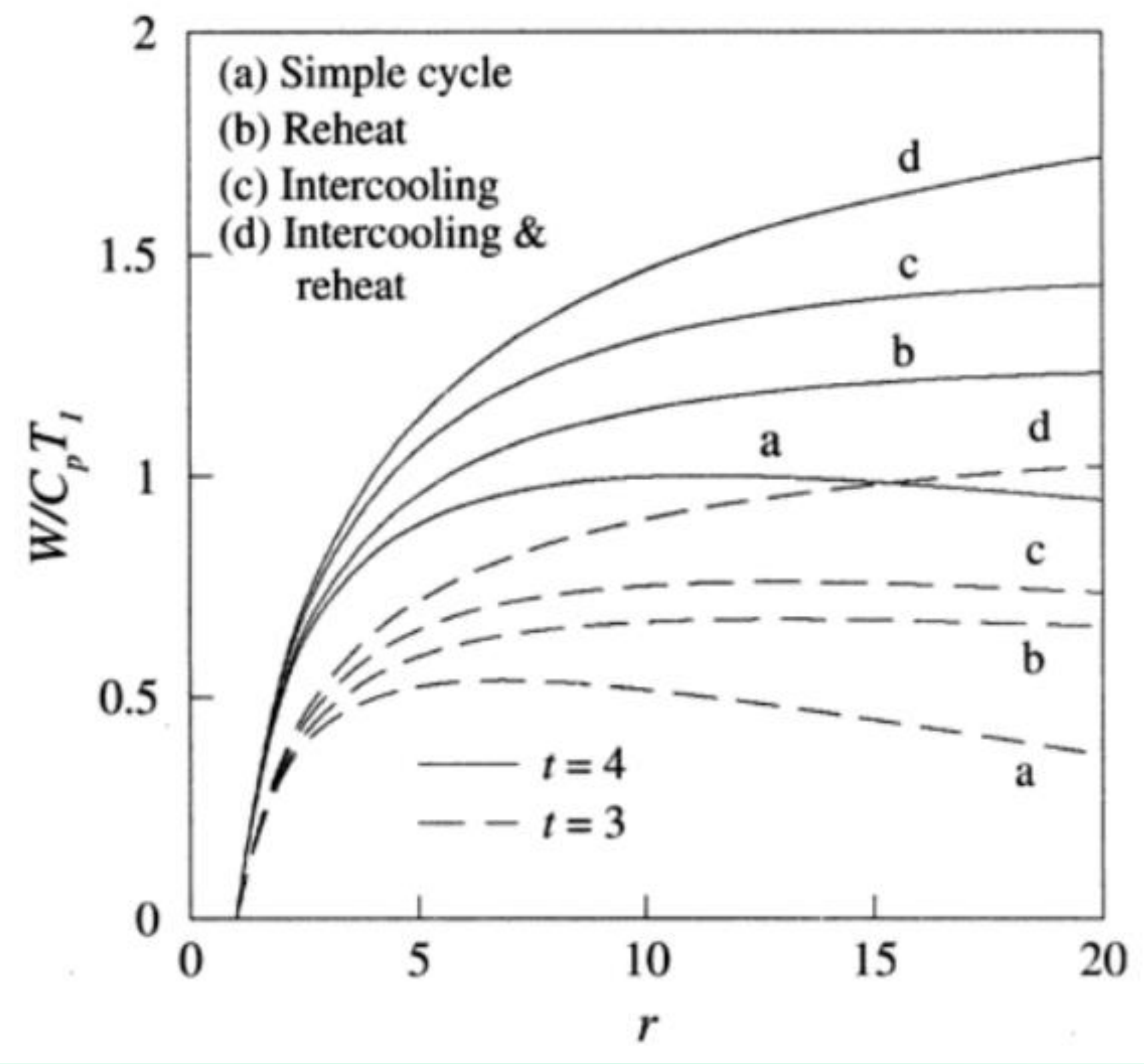




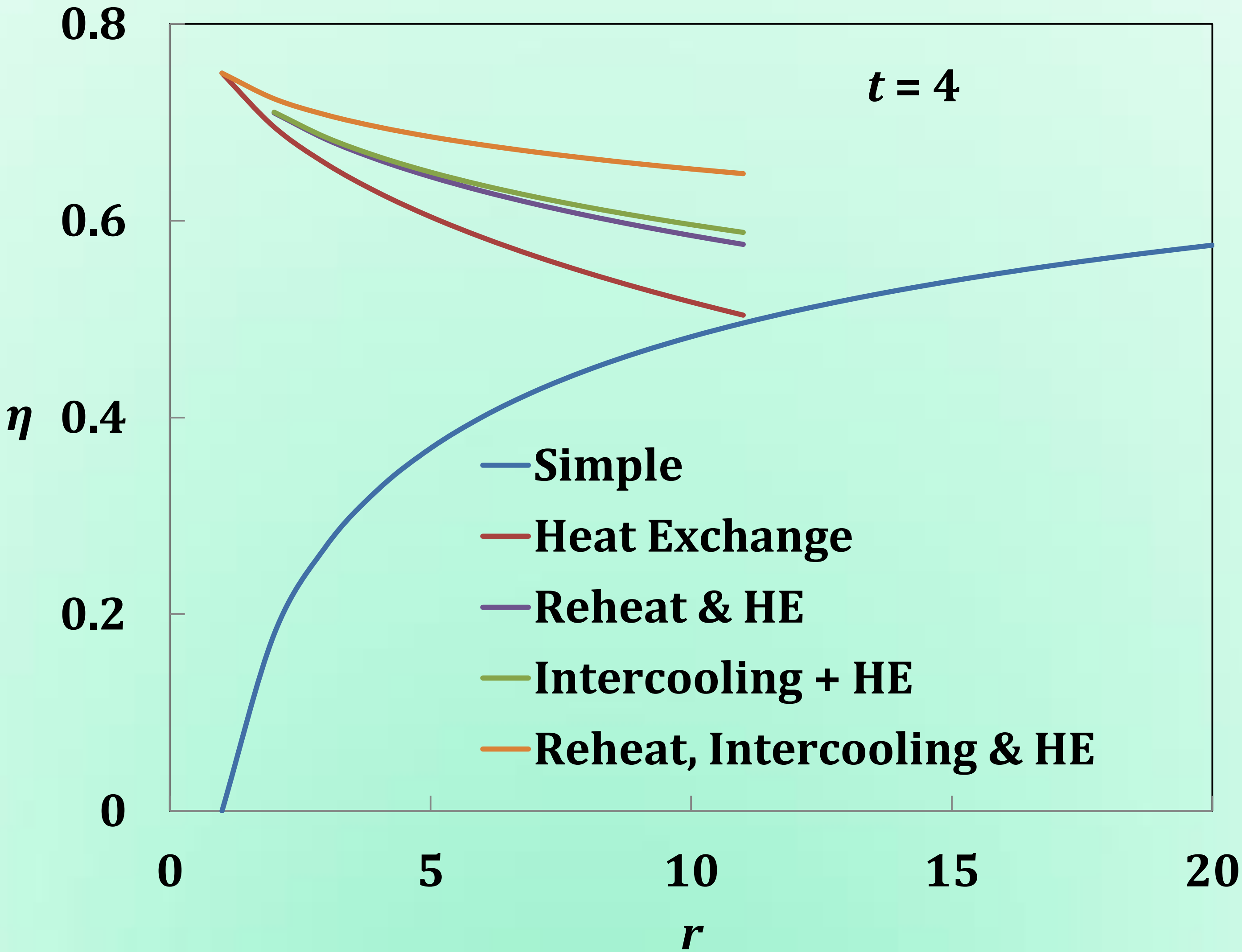
Intercooled, Reheat & Heat Exchange: Efficiency



Comparison: Specific Work Output



Comparison: Efficiency



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

S.No.	Addition to simple cycle	Effect on η	Effect on $\frac{W}{C_p T_1}$
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%