Energy Conservation and Waste Heat Recovery

Structure

- Approximately 40+ lectures each of 1 hour duration
- Each of the two instructors will cover almost half of the content
- Two class tests
- Some assignments
- Mid-sem & end-sem exams

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Source of Information

- Heat Recovery systems by D. A. Reay, E & F.N.Span, London, 1979
- Waste Heat Recovery Methods and Technologies, C.C.S. Reddy and S.V. Naidu, Andhra University; G.P. Rangaiah, Chemical Engineering, January 1, 2013
- https://beeindia.gov.in/sites/default/files/2Ch8.pdf (Bureau of energy Efficiency, Govt. of India)
- Waste Heat Recovery: Technology and Opportunities in U.S. Industry by U.S. Department of Energy, Industrial Technologies Program, March 2008
- Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities by Oak Ridge National Laboratory, December 25, 2014

Web document released by Industry:

Waste Heat Recovery – Optimizing your energy system *by Alfa Laval*

Prerequisites

Fundamental knowledge of Thermodynamics, Heat Transfer and Fluid Flow

What is Energy Conservation and Waste Heat Recovery?

Energy Conservation (EC): Reduction in the amount of energy consumed in a process or system, or by an organization or society, through proper design and planning, economy, rational use, elimination of waste, and *recovery.*

Waste Heat: thermal energy dumped by a process or a equipment to the environment, even though it has a potential to be used profitably.

Waste Heat Recovery (WHR): Waste heat recovery is the collection of heat created as an undesired by-product of the operation of a piece of equipment or machinery to serve a desired purpose elsewhere.

Why Waste Heat Recovery?

Let us look into its potential….

Volcanoes are extraordinary sources of energy. For example, the Laki eruption of 1783 in southern Iceland produced 15 km3 of lava. The heat released from the lava measured 80 exajoules; enough energy to keep all the world's industries running for six months …

Taken from a web document released by Alfa Laval

Potential of Waste Heat Recovery

- ❖ By some estimation the amount of waste heat for an average industry is 20-50% of energy consumption

- ❖ By the estimation of International Energy Agency (IEA) 50% of the energy consumed by all the industries is released as waste heat

- So, there is an enormous potential. According to some opinion WHR can compete well with renewables
- In certain industries WHR is absolutely essential to be competitive. Examples: petroleum refinery, air separation plant

Sectors where the potential exists

Energy usage

- ❖Industrial
- ❖Commercial
- ❖Domestic

Maximum effort for WHR has been made in industrial sector as obviously the potential is the highest.

The other two sectors are unexplored though there may be some potential for WHR.

Potential Industries:

Power – Fossil Fuel and Nuclear

Process – Refineries, petrochemicals, Chemicals, Cement, Glass, etc.

Transportation

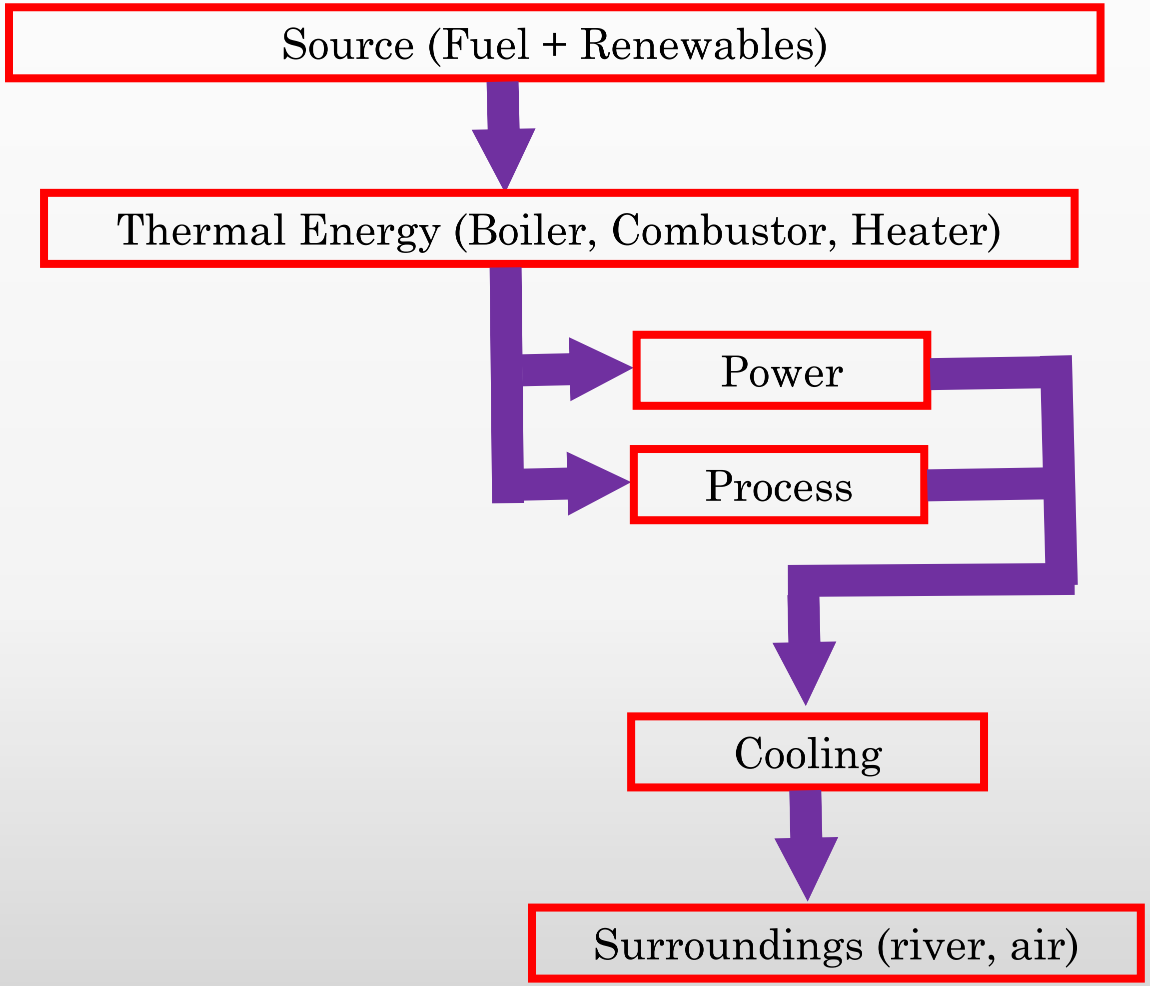
Metallurgy and manufacturing – Steel, Aluminium, Molding, Sintering, Extrusion, Hot forming

Food and Beverages

Cooling Processes - HVAC, Refrigeration and Cryogenics

WHR explained

Energy flow **without** Waste Heat Recovery



Source (Fuel + Renewables)

Thermal Energy (Boiler, Combustor, Heater)

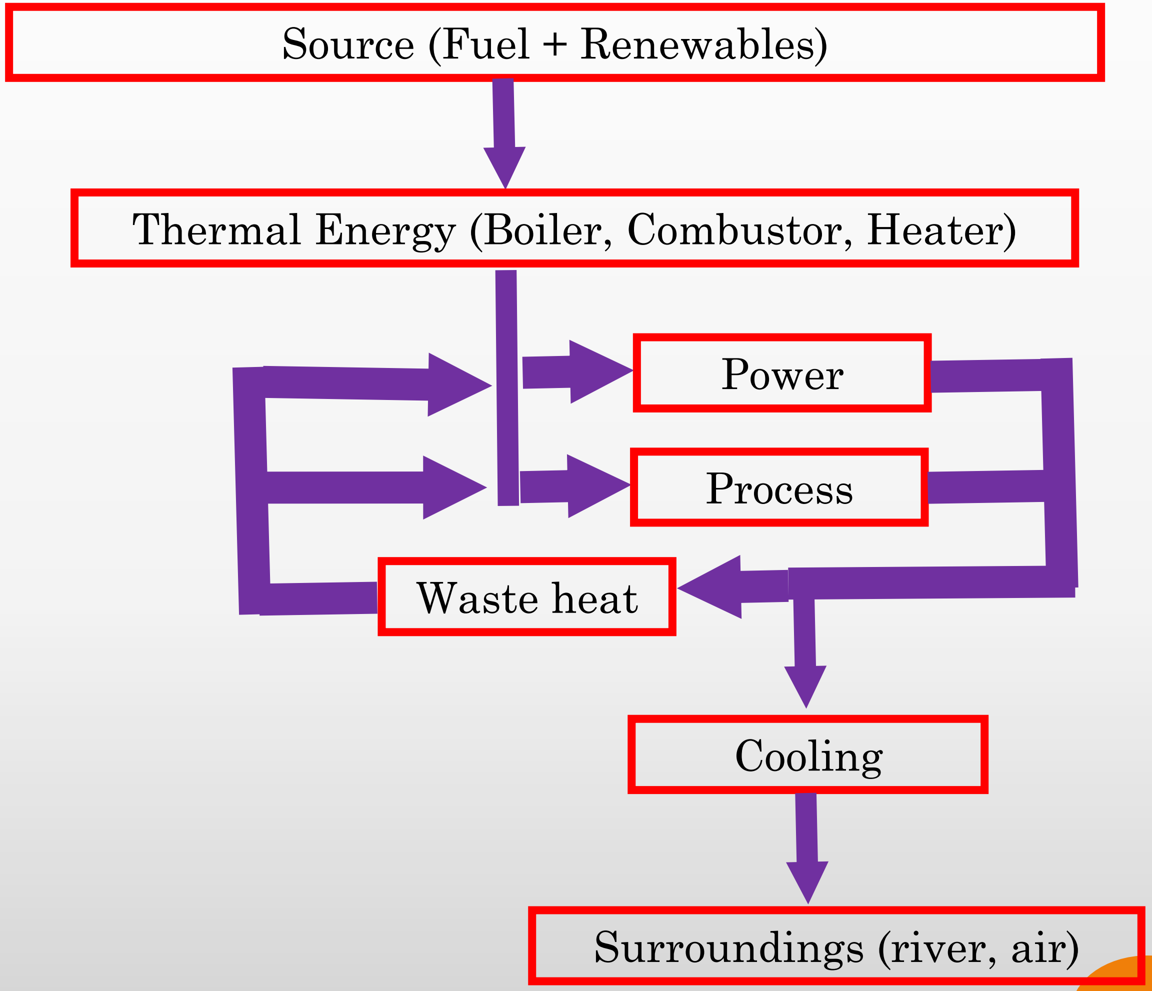
Power

Process

Cooling

Surroundings (river, air)

Energy flow **with** Waste Heat Recovery



Source (Fuel + Renewables)

Thermal Energy (Boiler, Combustor, Heater)

Power

Process

Waste heat

Cooling

Surroundings (river, air)

Reasons for Generation of Waste Heat

- Thermodynamic limitation of process and equipment.
- Physical limitation of equipment.
- Characteristics and chemical composition of exhaust streams.
- Minimum allowable temperature of cooling
- Plant layout and space available.
- Economy and energy policy.
- Scope of profitable use of waste heat.

Sources of Waste Heat

- Hot exhaust and effluents.
- Hot streams needed for cooling.
- Hot products(in metallurgical, process and chemical industries).
- Hot surfaces of furnaces and incinerators.

Though WHR from first two sources has been well exercised recovery from the two other sources are grossly unexplored. If the full potential of the two other sources are recovered fuel bill can be cut down to a considerable amount.

Important Characteristics Of Waste Heat

- Quantity
- Quality

Strategies of WHR

The best strategy for WHR is the least production of waste heat. If the production of waste heat is unavoidable, different ways of WHR should be adopted.

Two possibilities exist

- Adoption of WHR principles at the design stage of a new plant.
- Retrofitting WHR technique is an existing plant. In general WHR techniques have acceptable pay back period.

Utilization Of Waste Heat

- ❖Generation of power
    - ❖Direct.
    - ❖Indirect (Through thermal to mechanical route)
- ❖Heating.
- ❖Cooling
- ❖Thermo compression
- ❖Enhancing the quality of thermal energy

Gains by WHR

There are number of primary gains by WHR and there are some secondary gains which follow from the primary ones. A non-exhaustive list of gains by WHR are as follows.

- ❖ Saving in fuel cost (Cost of electricity).
- ❖ Reduction in exhaust- CO_2, CO, NO_x, SO_x, unburnt hydrocarbon. Industry can gain credit by reduction of emission if that is applicable.

- Increase in process efficiency: air preheating or heating of fuel oil improves combustion efficiency. Higher temperature may be achieved.

- Reduction in plant size: as demand of energy supply reduces, the size of many primary and secondary systems reduces.

- Reduction in cooling (heat rejection) system: as the heat rejection reduces, there is reduction in cooling water system, cooling tower, water treatment plant, fans, heat exchangers etc.

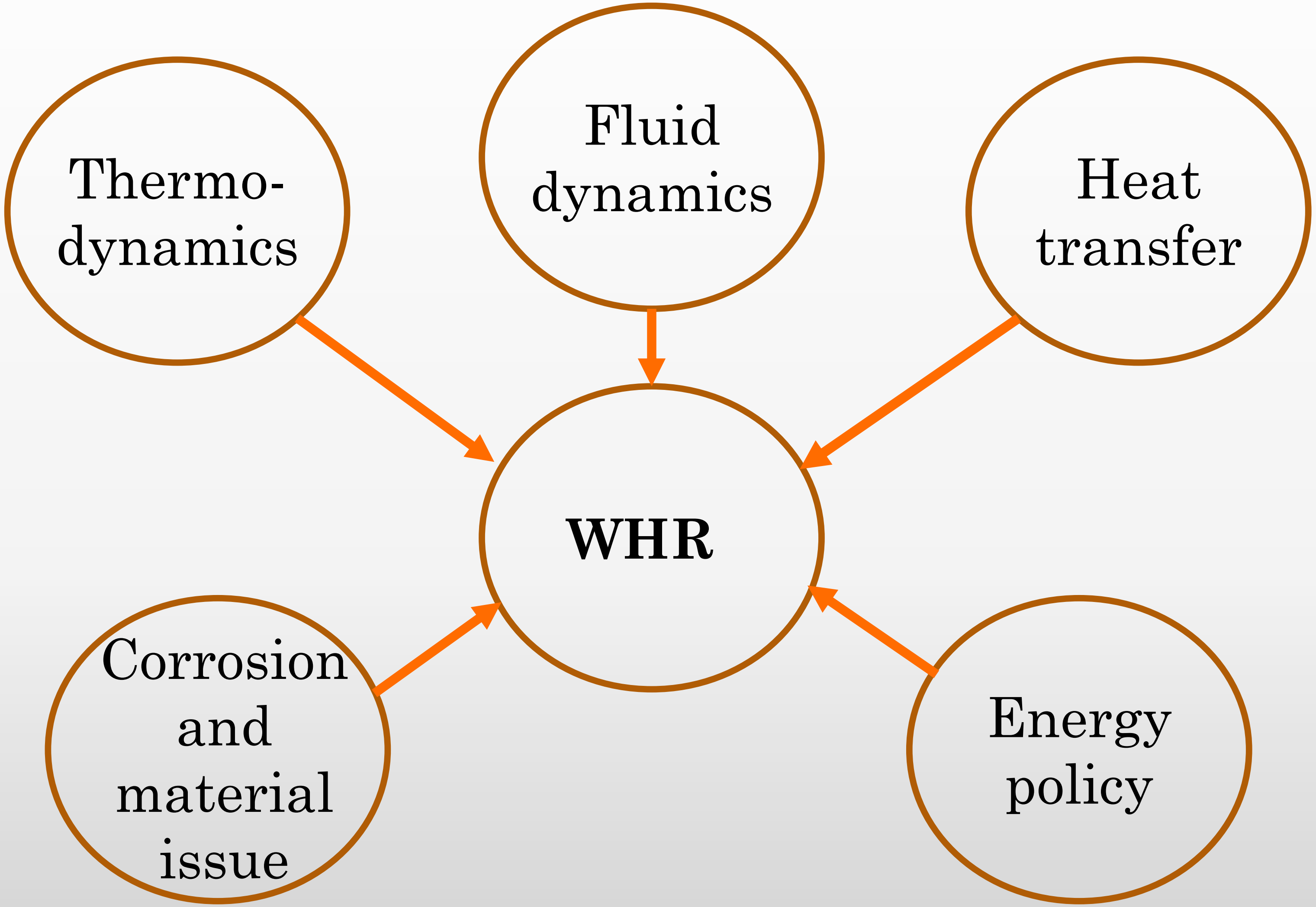
- Sometimes there are restrictions for the highest temperature and amount of exhaust, amount of cooling water to be taken etc. WHR helps in having a better compliance with the environment standard.

Further, WHR helps in reducing stack height and reduces the use of the auxiliary power and by-product consumption.

- Reduction of capital cost if WHR is adopted from the design stage of the plant.

- Production of additional cooling

Design of WHR system



Relationship of WHR with other Energy Issues

Some Useful Terminologies

- Sustainibility: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

It may also be defined as a requirement of our generation to manage the resource base such that the average quality of life that we ensure ourselves can potentially be shared by all future generations. [Geir B. Asheim, "Sustainability," The World Bank, 1994]

- Energy Security: The IEA defines *energy security* as “the uninterrupted availability of *energy* sources at an affordable price”.

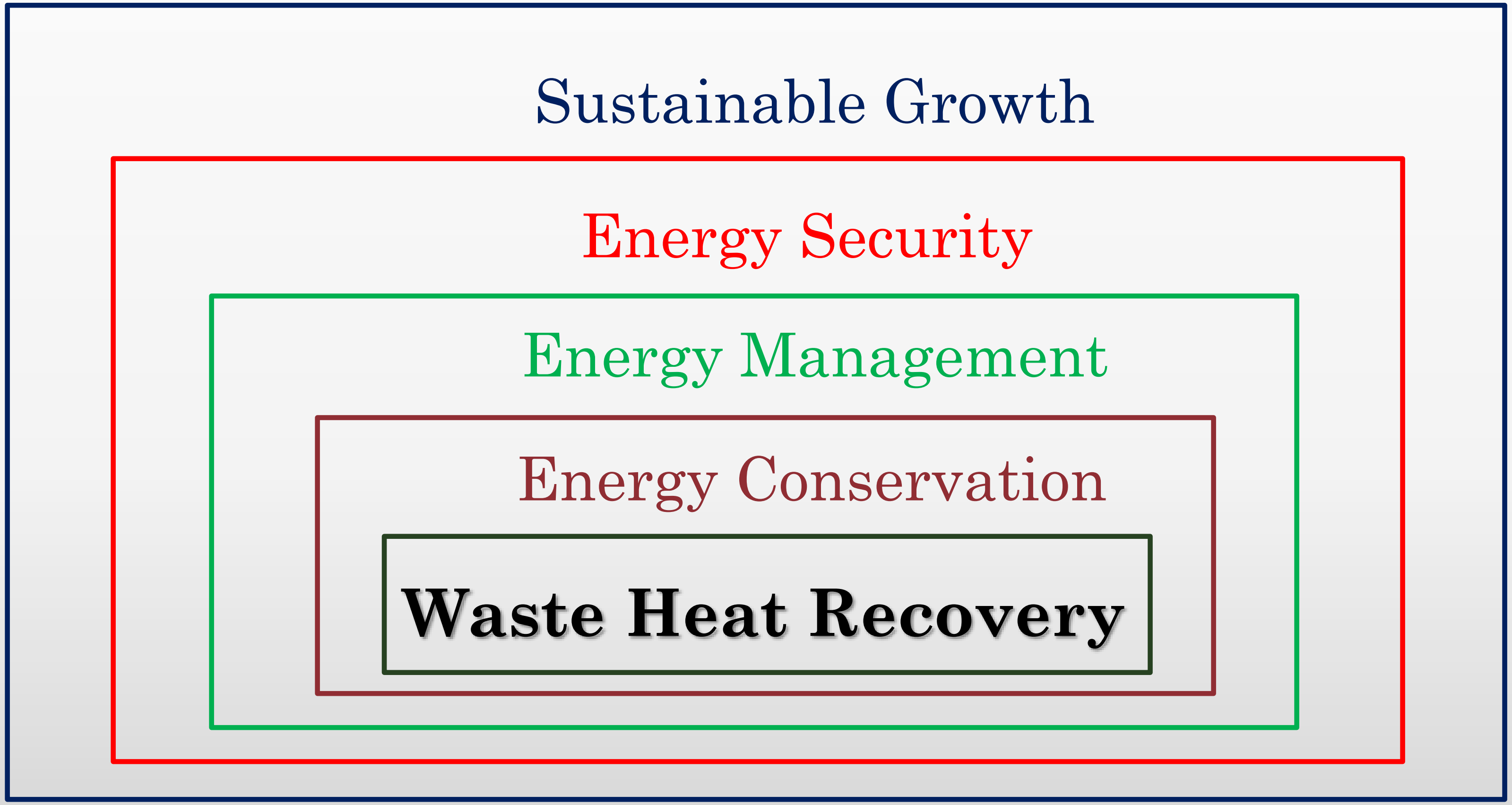
- **Energy Management**: The strategy of adjusting and optimizing energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems.(energy management association of Newzeland)

- **Passive Technique**: Principles of heating and cooling without using any /using minimal amount of auxiliary power.

- **Energy Audit**: Methodologies for assessing wasteful use of energy including thermal energy. It often gives an measure of waste heat.

- **Energy Storage**: At a particular instant, the amount of energy generated and energy demand may not match. So then, energy storage is required to cater for the excess demand or to store the excess generation. This is one of the essential components of energy systems.

Waste Heat Recovery in the perspective of Energy activity



Sustainable Growth

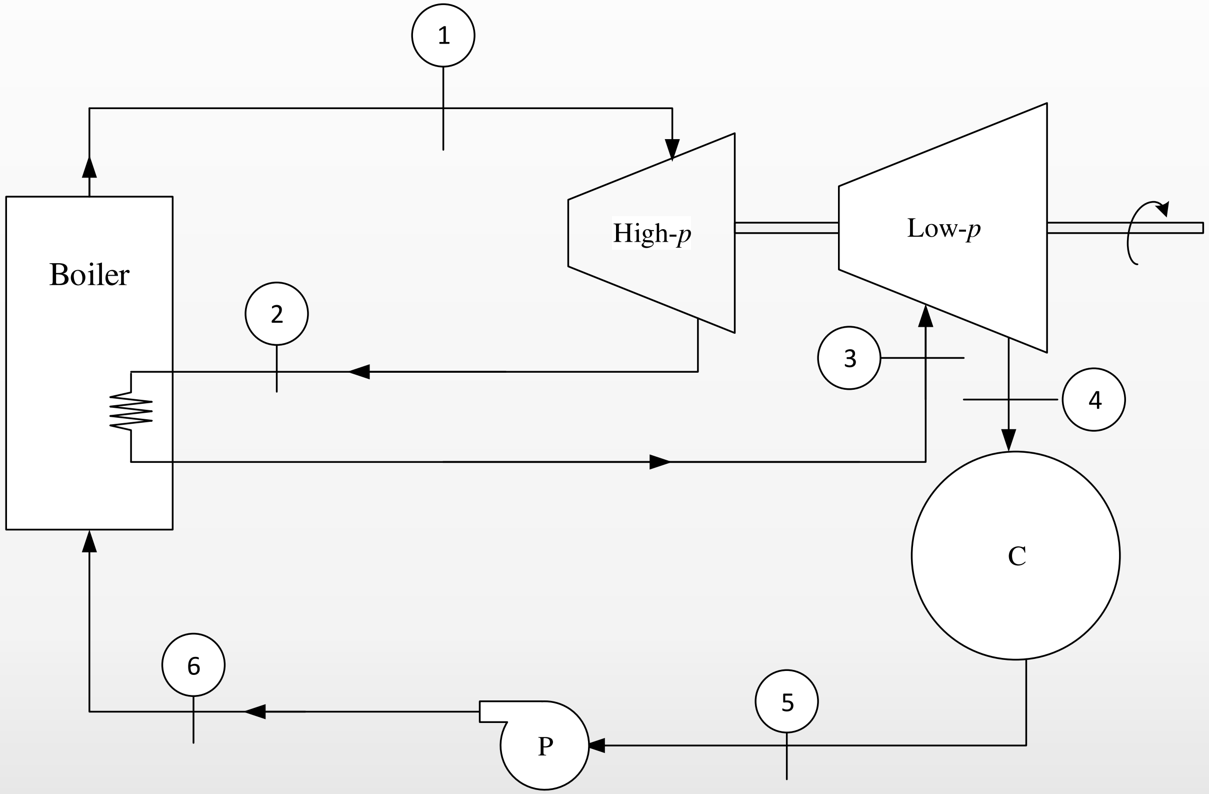
Energy Security

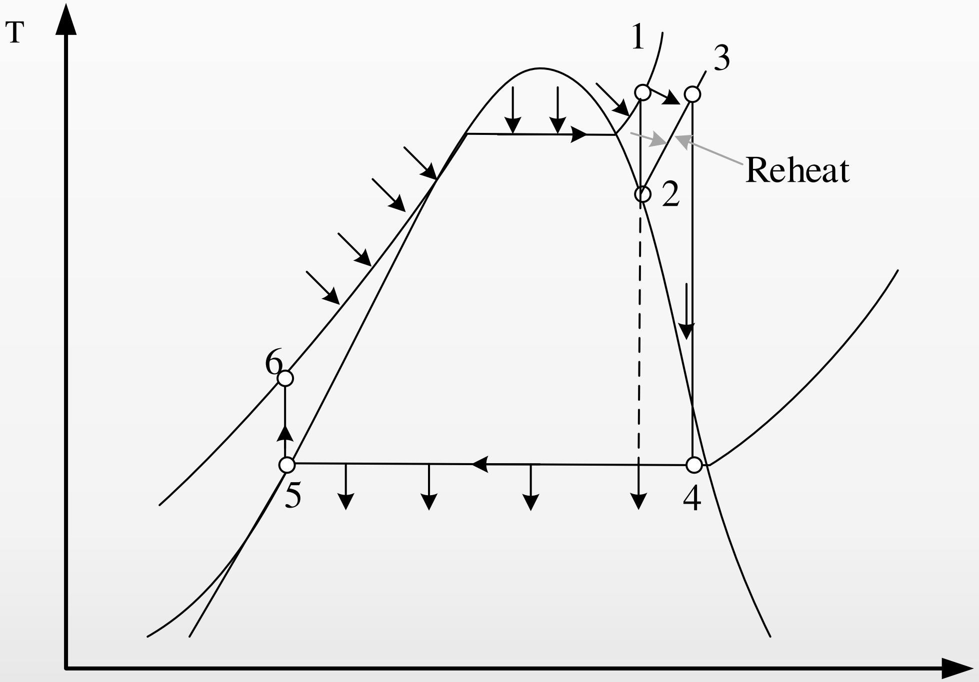
Energy Management

Energy Conservation

Waste Heat Recovery

Rankine cycle with Reheating





Rankine cycle with Reheating: An example

A power plant operates on an ideal reheat Rankine cycle. Steam enters the high pressure turbine at 15 MPa, 525 ºC with a flow rate of 100 kg/s and exits as saturated vapor. The quality of steam at the exit of the second-stage turbine is 90% and the condenser pressure is 8 kPa. Determine (a) the reheat pressure, (b) the reheat temperature and (c) the thermal efficiency.

State	Given	h (kJ/kg)	State	Given	h (kJ/kg)
1	p_1, T_1, $\dot{m}_1$	3379	4	p_4, $x_4 = 0.9$	2337
2	x_2, $s_2 = s_1$	2793 P = 1.56 MPa	5	$p_5 = p_4$, $x_5 = 0$	174
3	$p_3 = p_2$, $s_3 = s_4$	h = 3409 T = 471 °C	6	$p_6 = p_1$, $s_6 = s_5$ or $h_6 = h_5 +$ $v_{f@T5} (p_6 – p_5)$	189.0

Thermodynamics an interactive approach
By Subrata Bhattacharjee, Pearson, 2015

Device	$\dot{Q}_1$ (MW)	$\dot{W}_{ext}$ (MW)	Device	$\dot{Q}_1$ (MW)	$\dot{W}_{ext}$ (MW)
A: Turbine-I (1-2)	0	58.53	D: Condenser (4-5)	-216.3	0
B: Reheater (2-3)	61.62	0	E: Pump (5-6)	0	-1.51
C: Turbine-II (3-4)	0	107.3	F: Boiler (6-1)	319.0	0

The thermal efficiency is:

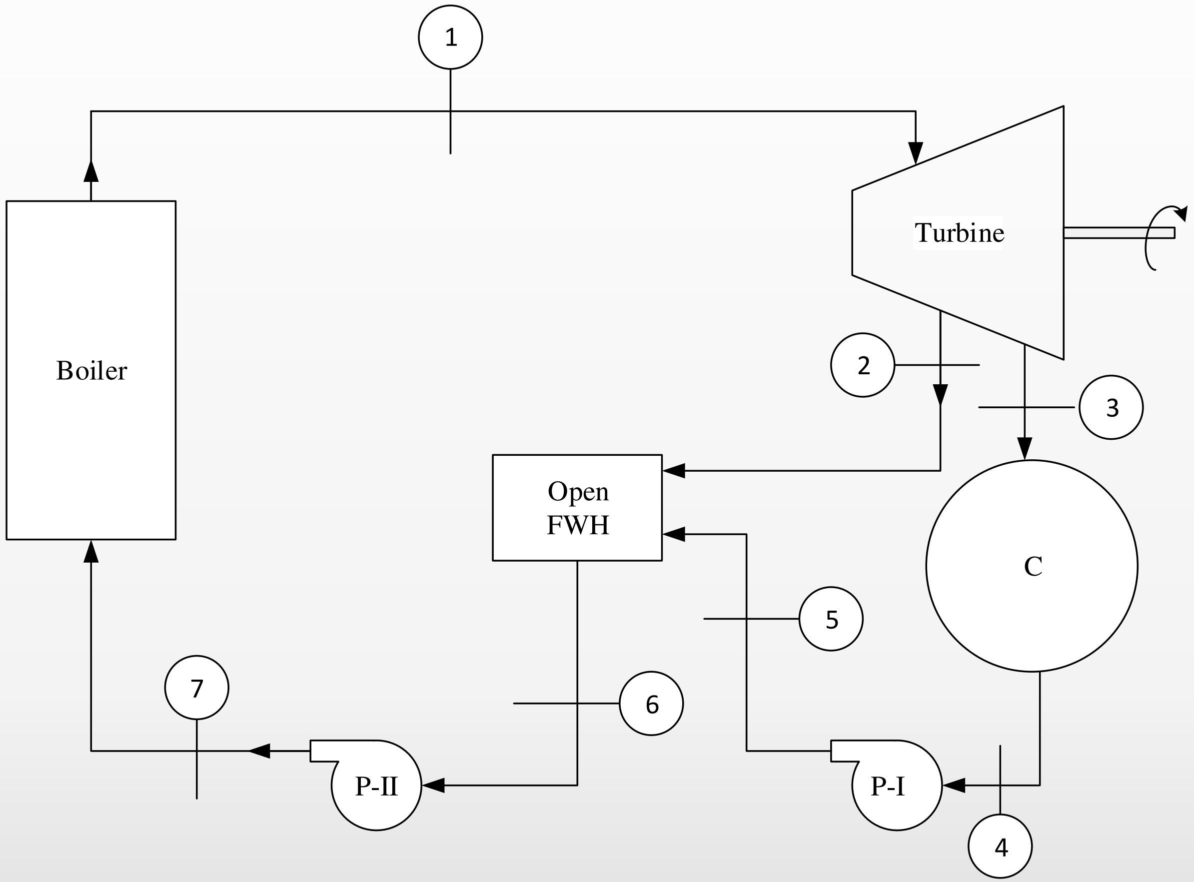
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

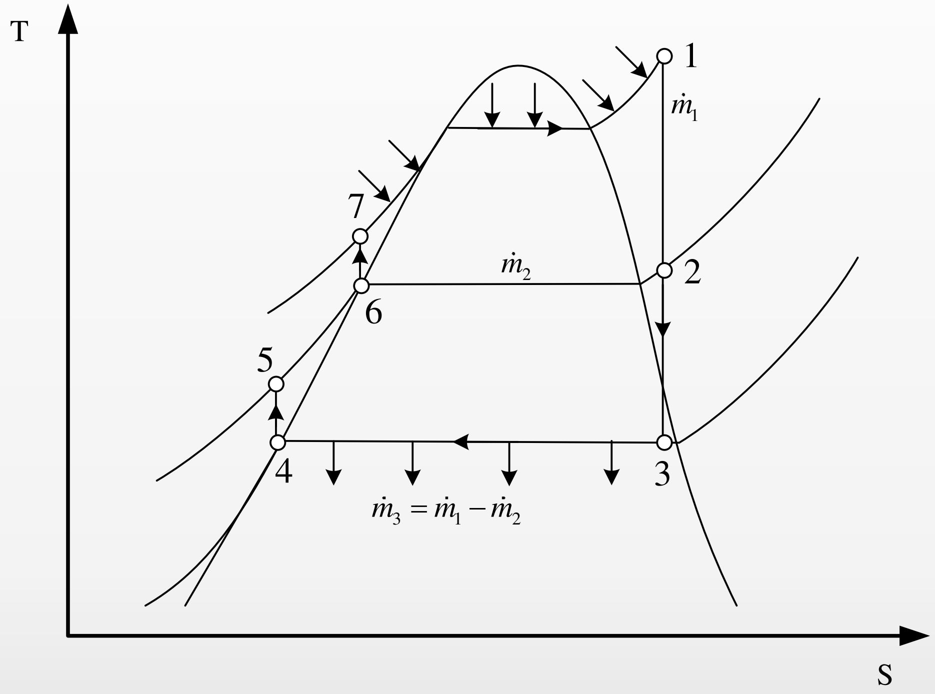
$$= 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

$$= 1 - \frac{216.3}{319 + 61.62}$$

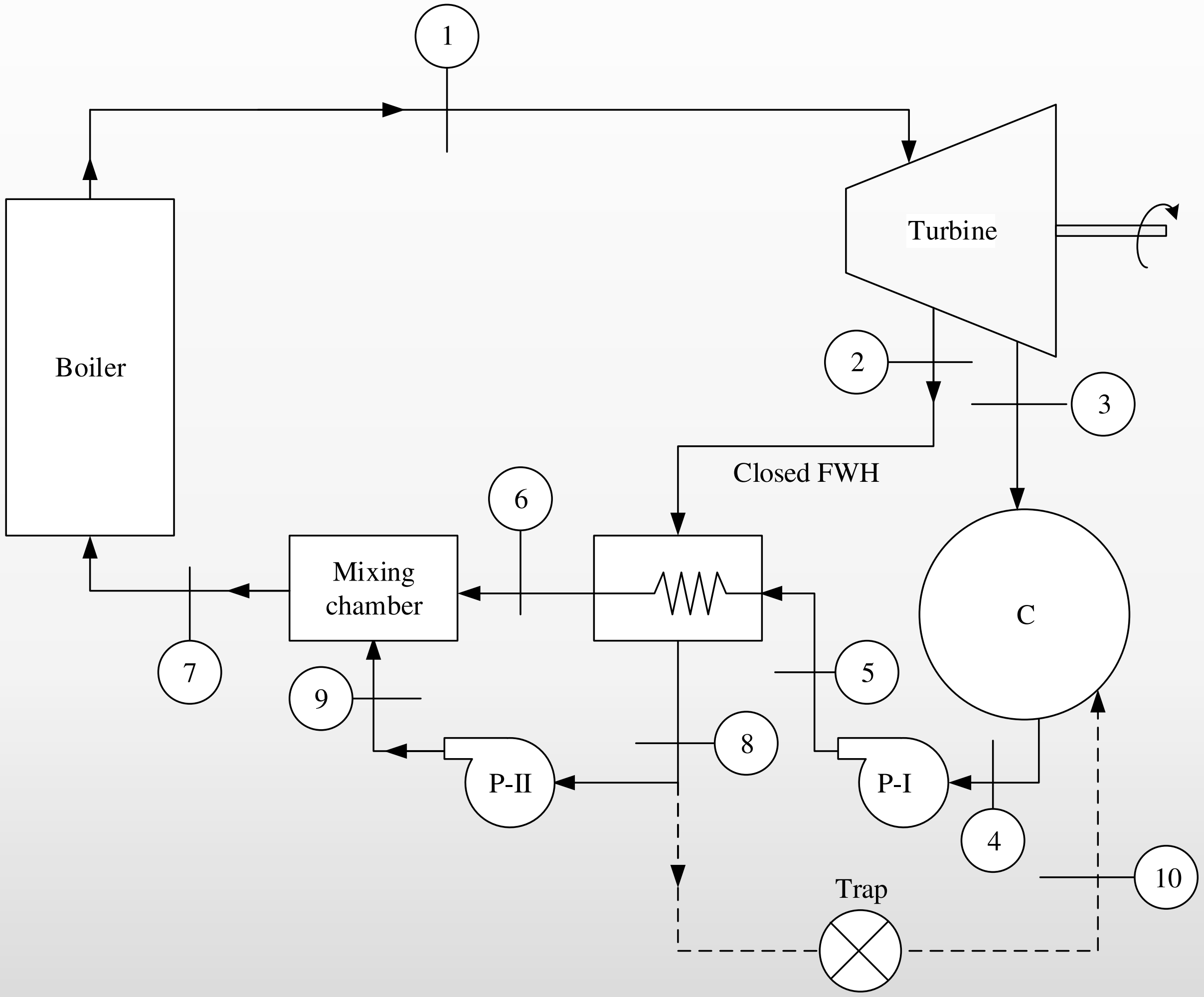
$$= 43.17\,\%$$

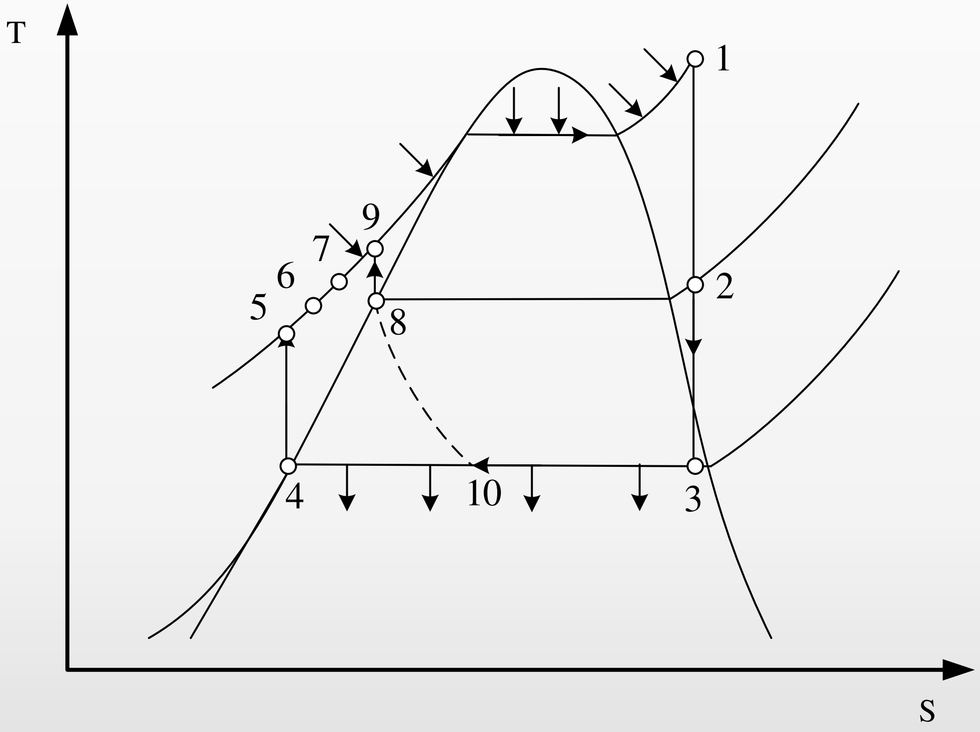
Rankine cycle with Regeneration (open feed water heater)





Rankine cycle with Regeneration (closed feed water heater)





Rankine cycle with Regeneration (open feed water heater): An example

A steam power plant operates on an ideal regenerative Rankine cycle with a single open feed-water heater. The turbine inlet conditions are 10 MPa, 650 ºC and the condenser pressure is 10 kPa. If bleeding takes place at 2 MPa, determine (a) the fraction of total flow through the turbine that is bled and (b) the thermal efficiency.

Thermodynamics an interactive approach
By Subrata Bhattacharjee, Pearson, 2015

State	Given	h (kJ/kg)	State	Given	h (kJ/kg)
1	p_1, T_1	3748	6	$p_6 = p_2$, $x_6 = 0$	908.8
2	p_2, $s_2 = s_1$	3191	7	$p_7 = p_1$, $s_7 = s_6$ or $h_7 = h_6 + v_{f@T6}$ $(p_7 - p_6)$	918.2
3	p_3, $s_3 = s_1$	2230			
4	$p_4 = p_3$, $x_4 = 0$	191.8			
5	$p_5 = p_2$, $s_5 = s_4$ or $h_5 = h_4 + v_{f@T4}$ $(p_5 - p_4)$	193.8			

An energy balance on the Feed Water Heater yields:

$$r=\frac{h_6-h_5}{h_2-h_5}=\frac{908.9-193.8}{3191-193.8}=0.239$$

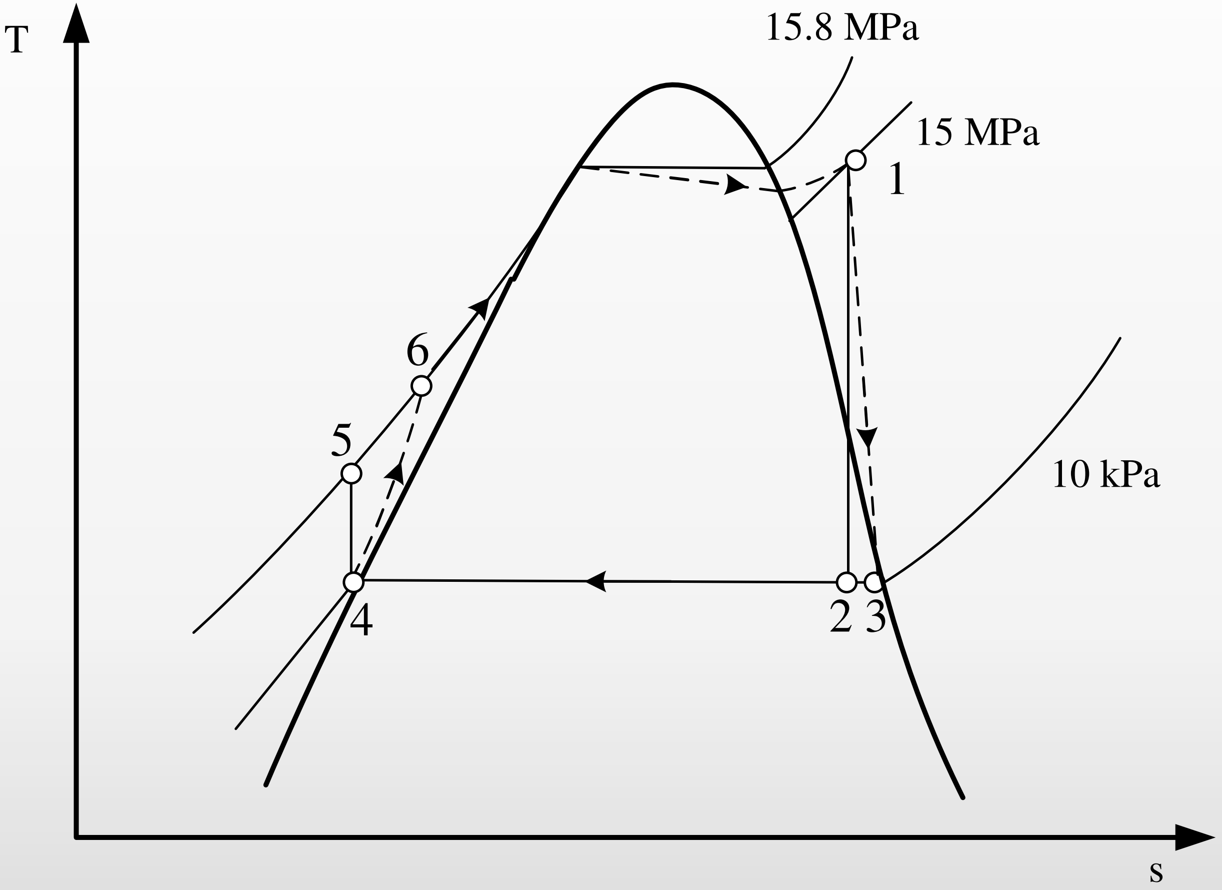
The thermal efficiency is obtained:

$$\eta_{th}=1-\frac{\dot{Q}_{out}}{\dot{Q}_{in}}=1-\frac{\dot{m}_1(1-r)(h_3-h_4)}{\dot{m}_1(h_1-h_7)}=1-\frac{(0.761)(2038)}{3748-918.2}=45.19\%$$

Rankine cycle with Irreversibilities: An example

A power plant operates on a simple Rankine cycle producing a net power of 100 MW. The turbine inlet conditions are 15MPa and 600 ºC and the condenser pressure is 10 kPa. If the turbine and pump each have an isentropic efficiency of 85% and there is a 5% pressure drop in the boiler, determine (a) the thermal efficiency, (b) the mass flow rate of steam in kg/h and (c) the back-work ratio.

Thermodynamics an interactive approach
By Subrata Bhattacharjee, Pearson, 2015


T
15.8 MPa
15 MPa
1
6
5
10 kPa
4
2
3
s

State	**Given**	**h (kJ/kg)**	**State**	**Given**	**h (kJ/kg)**
1	p_1, T_1	3582	4	$p_4 = p_2$ $x_4 = 0$	191.8
2	p_2, $s_2 = s_1$	2115	5	$p_5 = p_1/0.95$, $s_5 = s_4$ or $h_5 = h_4 +$ $v_{f@T4}$ $(p_5 – p_{4)}$	207.8
3	$p_3 = p_2$, $h_3 = h_1 –$ $(h_1 - h_2)/\eta_T$	2408	6	$p_6 = p_5$, $h_6 = h_4 +$ $(h_5 – h_4)/\eta_P$	211.8

Device	$\dot{Q}/\dot{m}$ (MJ/kg)	$\dot{W}_{ext}/\dot{m}$ (MJ/kg)	Device	$\dot{Q}/\dot{m}$ (MJ/kg)	$\dot{W}_{ext}/\dot{m}$ (MJ/kg)
A: Turbine (1-3)	0	1.174	C: Pump (4-6)	0	-0.020
B: Condenser (3-4)	-2.217	0	D: Boiler (6-1)	3.371	0

The mass flow rate of steam, now, can be obtained as:

$$\dot{W}_{net} = \dot{W}_T - \dot{W}_P \quad = \dot{m}\left(\frac{\dot{W}_T}{\dot{m}} - \frac{\dot{W}_P}{\dot{m}}\right) \quad \Rightarrow \dot{m} = \frac{100}{1.174 - 0.02} = 86.65\, kg/s$$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{100}{(3.371)(86.65)} = 34.2\%$$

Back-work ratio = $\dfrac{\dot{W}_T}{\dot{W}_P} = 1.7\%$

Rankine cycle Exergy Accounting: An example

A power plant operates on a simple Rankine cycle producing a net power of 100 MW. The turbine inlet conditions are 15MPa and 600 ºC and the condenser pressure is 10 kPa. The turbine and pump each have an isentropic efficiency of 85% and there is a 5% pressure drop in the boiler. Assume the heat addition from the reservoir to take place at 1500 K and heat rejection to a reservoir at 310 K. The atmospheric conditions are 100 kPa and 300 K. Do an exergy analysis of the cycle.

Thermodynamics an interactive approach
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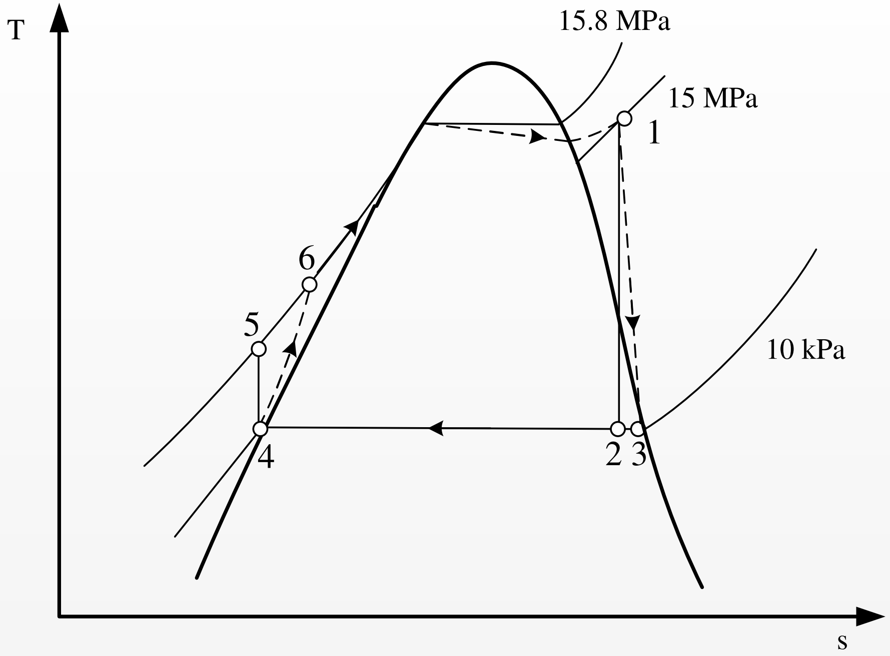
Solution:



Exergy supplied to the working fluid in the boiler:

$$\dot{Q}_{in}\left(1-\frac{T_0}{T_H}\right)=(292{,}072)\left(1-\frac{300}{1500}\right)=233{,}658\,kW=233.66\,MW$$

Exergy gained by the working fluid from heat addition:

$$\Rightarrow \dot{m}\left[\left(h^0-T_0\,s\right)_1-\left(h^0-T_0\,s\right)_6\right]=135.68\ MW$$

Exergy destroyed during heat addition:

$$\dot{I} = 233.66 - 165.68 = 97.98\,MW$$

Exergy delivered to the turbine by the working fluid:

$$\Rightarrow \dot{m}\left[\left(h^0 - T_0\, s\right)_1 - \left(h^0 - T_0\, s\right)_3\right] = 125.64\ MW$$

Exergy delivered by the turbine to the shaft = 101.73 MW

Exergy destroyed in the turbine = 125.64 – 101.73 = 23.91 MW

Exergy lost by the steam to the condenser:

$$\Rightarrow \dot{m}\left[\left(h^0 - T_0\, s\right)_3 - \left(h^0 - T_0\, s\right)_4\right] = 11.443\ MW$$

Exergy transferred by the heat lost in the condenser:

$$\dot{Q}_{out}\left(1-\frac{T_0}{T_C}\right)=(192.07)\left(1-\frac{300}{310}\right)=6.20\,MW$$

Exergy destroyed during heat rejection:

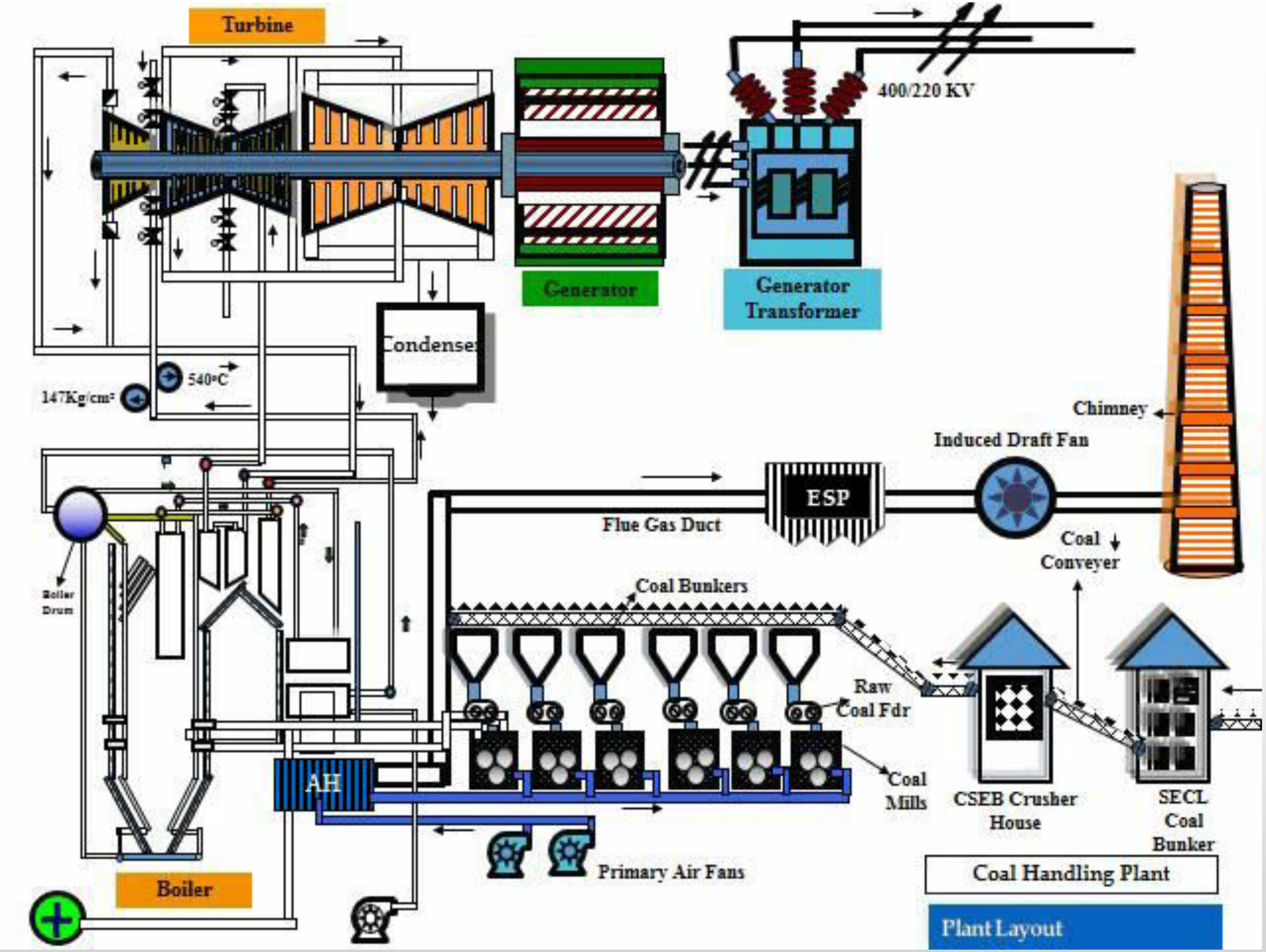
$$\dot{I}=11.443-6.20=5.243\,MW$$

Exergy gained by water in the pump:

$$\Rightarrow \dot{m}\left[\left(h^0-T_0\,s\right)_6-\left(h^0-T_0\,s\right)_4\right]=1.404\ MW$$

Exergy input to the pump as shaft work = 1.726 MW

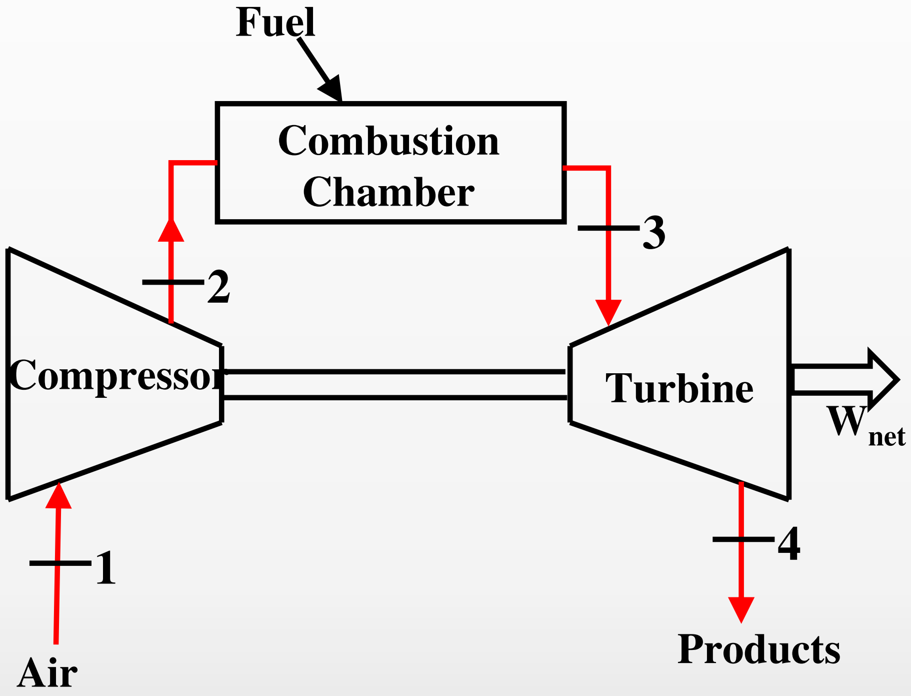
Exergy destroyed in the pump: $\dot{I}=1.726-1.404=0.322\,MW$


Turbine
Generator
Generator Transformer
400/220 KV
Condenser
540°C
147Kg/cm²
Boiler Drum
Chimney
Induced Draft Fan
ESP
Flue Gas Duct
Coal Conveyer
Coal Bunkers
Raw Coal Fdr
Coal Mills
CSEB Crusher House
SECL Coal Bunker
AH
Primary Air Fans
Boiler
Coal Handling Plant
Plant Layout

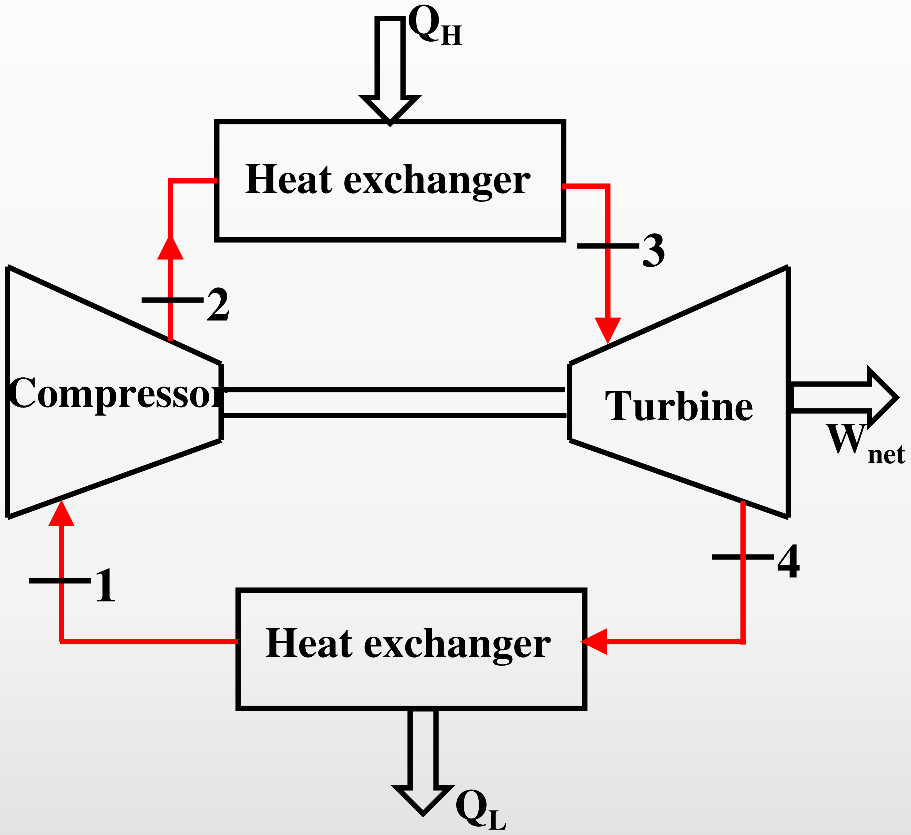
Gas Turbine Power Plant


MAN
MAN Diesel & Turbo

The Air-standard Brayton Cycle

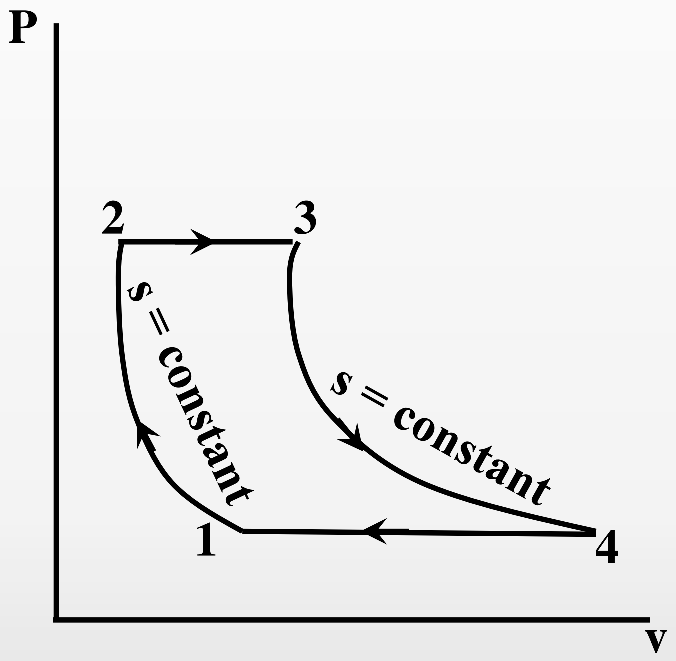


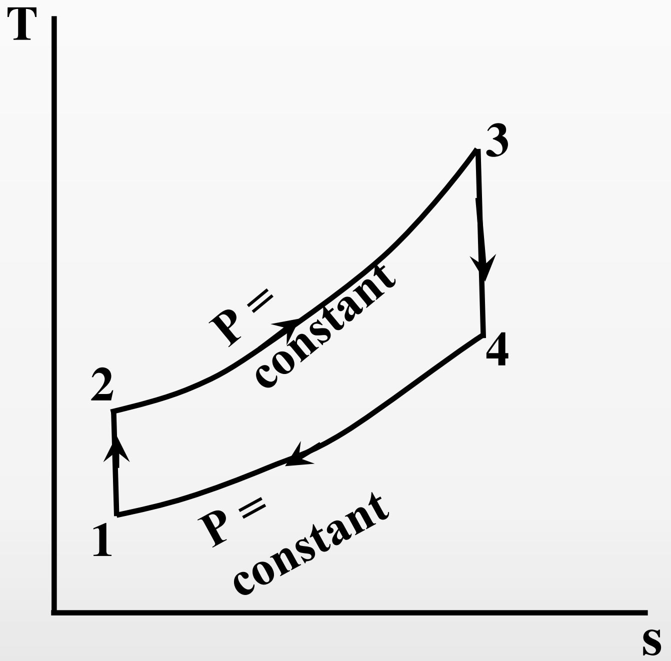
Open cycle



Closed cycle

The Air-standard Brayton Cycle





The efficiency of the air-standard Brayton cycle is found as:

$$\eta_{th} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{C_P\left(T_4 - T_1\right)}{C_P\left(T_3 - T_2\right)} = 1 - \frac{T_1\left(T_4 / T_1 - 1\right)}{T_2\left(T_3 / T_2 - 1\right)}$$

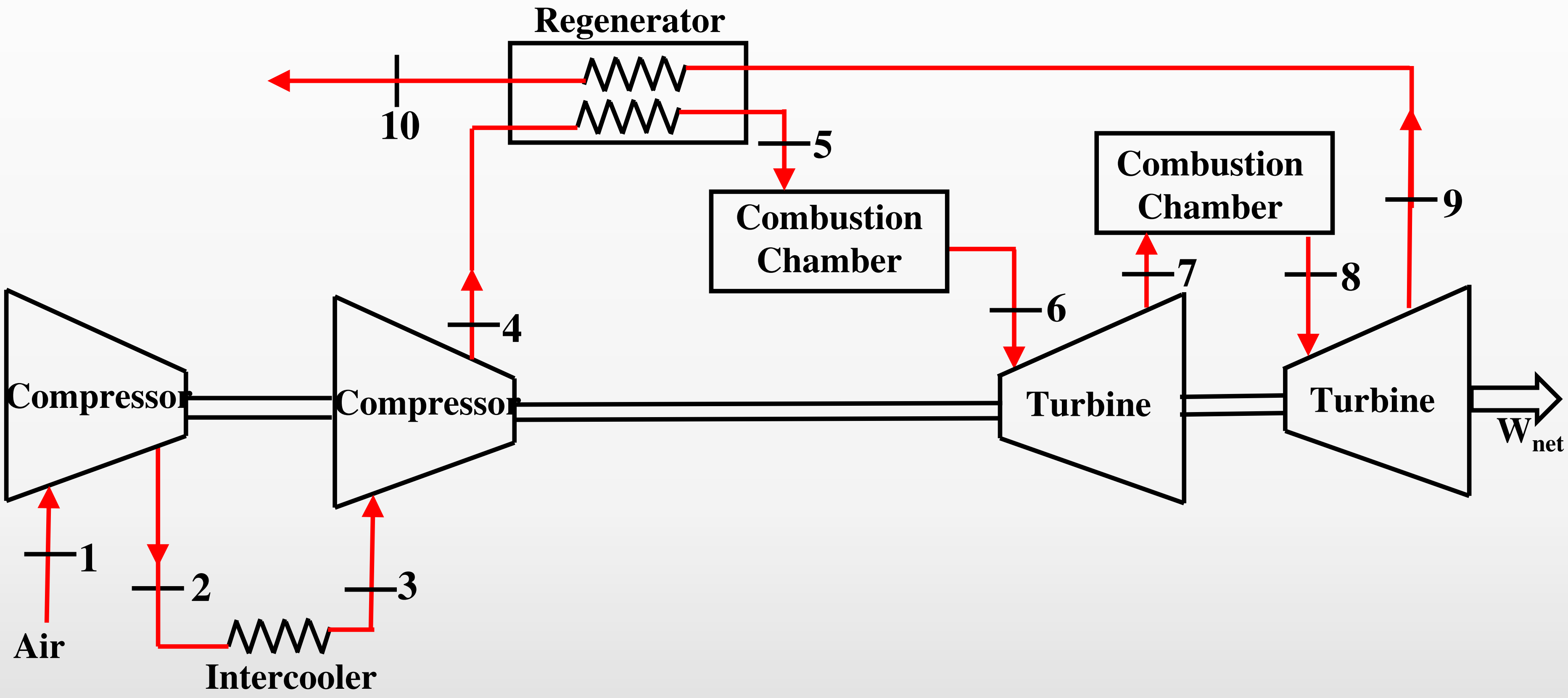
$$\frac{P_3}{P_4} = \frac{P_2}{P_1}$$

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

$$\frac{T_3}{T_4} = \frac{T_2}{T_1} \quad \therefore \frac{T_3}{T_2} = \frac{T_4}{T_1} \quad and \quad \frac{T_3}{T_2} - 1 = \frac{T_4}{T_1} - 1$$

$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\left(P_2 / P_1\right)^{(k-1)/k}}$$

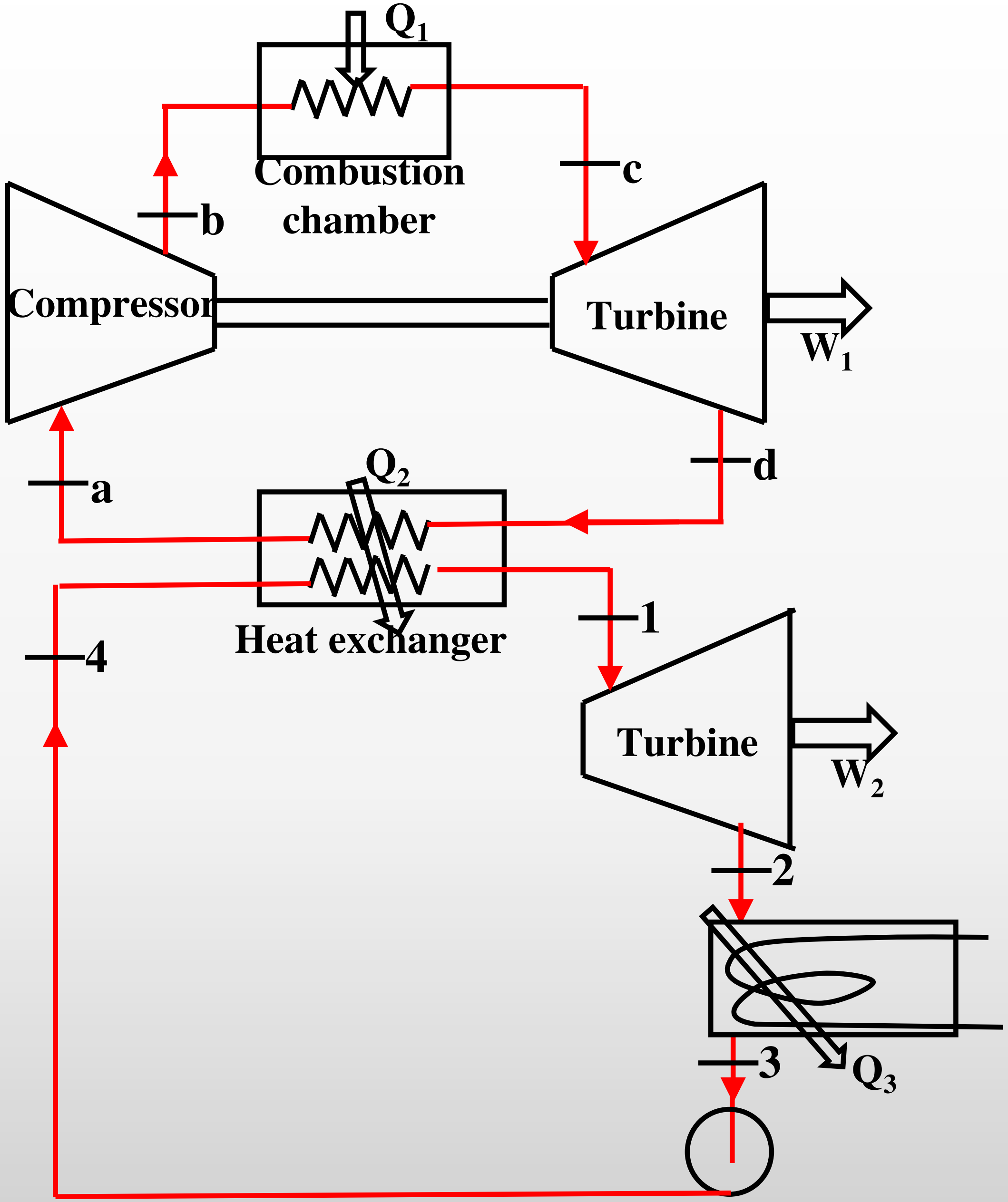
The gas-turbine cycle utilizing intercooling, reheat and a regenerator



Combined Cycle Power Plant

GT + SPP
MHD + SPP
TE + SPP
TI + SPP

Brayton-Rankine Combined Cycle Plant



Efficiency of Combined Cycle Power Plant:

Efficiency of Cycles in Series (Energy Cascading)

$$\eta_1 = 1 - \frac{Q_2}{Q_1} \qquad \eta_2 = 1 - \frac{Q_3}{Q_2}$$

$$\eta = 1 - (1-\eta_1)(1-\eta_2)$$

$$1-\eta = (1-\eta_1)(1-\eta_2)$$

For n cycles coupled in series, the overall efficiency is:

$$1-\eta = \prod_{i=1}^{n}(1-\eta_i)$$

Suppose, $\eta_1 = 0.55, \eta_2 = 0.55\, and\, \eta_3 = 0.45$

$$\eta = 1-(1-\eta_1)(1-\eta_2)(1-\eta_3)$$

$$= 1 - 0.45 \times 0.45 \times 0.55$$

$$= 0.89$$

Heat Loss between Two Plants in Series :

The overall plant efficiency would be:

$$\eta = \eta_1 + \eta_2 \frac{Q_3}{Q_1}$$

$$= \eta_1 + \eta_2 \left[\left(\left(1 - \eta_1 \right) \right) - \frac{Q_L}{Q_1} \right]$$

$$= \eta_1 + \eta_2 - \eta_1 \eta_2 - \eta_2 x_L$$

Q_L heat loss between two plants

$x_L = \frac{Q_L}{Q_1}$ fraction of the supplied heat which is lost

Two Plants in Series with Supplementary Firing:

The overall plant efficiency would be:

$$\eta = \eta_1 + \eta_2 - \eta_1 \eta_2 - x_2 \eta_1 (1 - \eta_2)$$

Q_4 supplementary heat

$x_2 = \dfrac{Q_4}{Q_1}$ fraction of the supplied heat which is used for supplementary heating

Advantages of Combined Cycle Power Plant (GT + SPP)

- High Thermal Efficiency
- Low Installed Cost
- Fuel Flexibility-Wide Range Of Gas and Liquid Fuels
- Low Operation and Maintenance Cost
- Operation Flexibility- Start up, Part load operation, Base, Mid-range, Daily start
- High Reliability
- High Availability
- Short Installation Cost
- High Efficiency in Small Capacity Increments

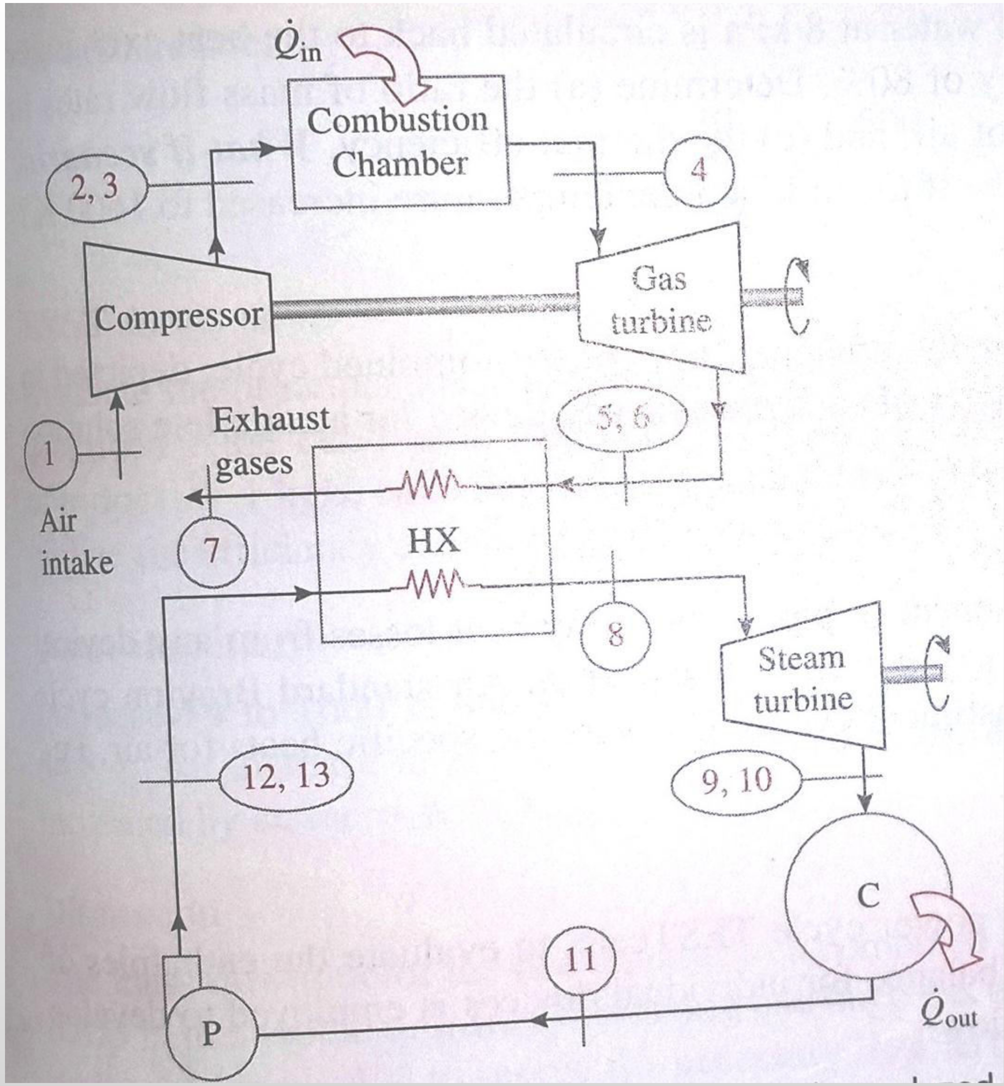
Combined Cycle Animation

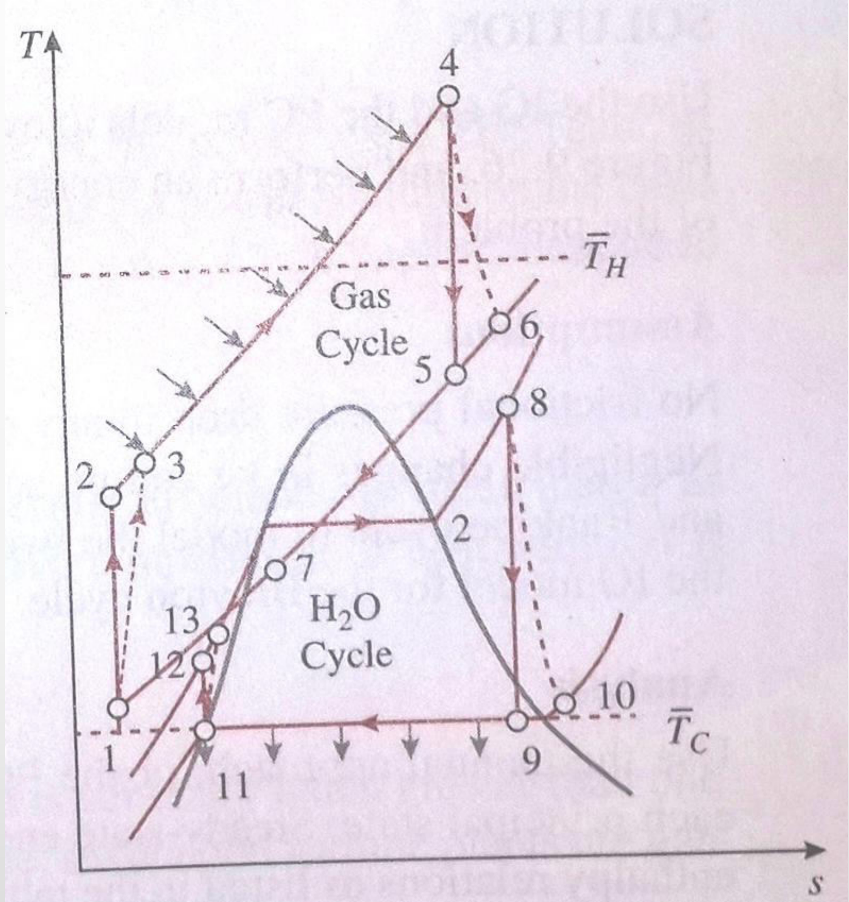
https://www.youtube.com/watch?v=jQ4yp_0Djvc

Combined Gas-Vapor Power Cycle: An example

A combined gas turbine-steam power plant produces a net power output of 500 MW. Air enters the compressor of the turbine at 100 kPa, 300 K. The compressor has a compression ratio of 12 and an isentropic efficiency of 85%. The turbine has an isentropic efficiency of 90%, inlet conditions of 1200 kPa, 1400 K and an exit pressure of 100 kPa. Air from the turbine exhaust passes through a heat exchanger and exits at 400 K. On the steam turbine side, steam at 8 MPa, 400 ºC enters the turbine, which has an isentropic efficiency of 85% and expands to the condenser pressure of 8 kPa. Saturated water at 8 kPa is circulated back to the heat exchanger by a pump with an isentropic efficiency of 80%. Determine (a) the ratio of mass flow rates in two cycles, (b) the mass flow rate of air and (c) the thermal efficiency.

Thermodynamics An interactive approach
By Subrata Bhattacharjee, Pearson, 2015





Thermodynamics An interactive approach
By Subrata Bhattacharjee, Pearson, 2015

State	Given	h (kJ/kg)	State	Given	h (kJ/kg)
1	p_1, T_1	1.9	8	p_8, T_8	3138.2
2	p_2, $s_2 = s_1$	311.7	9	p_9, $s_9 = s_8$	1990.0
3	$p_3 = p_2$, $h_3 = h_1 + (h_2 – h_1)/\eta_C$	366.5	10	$p_{10} = p_9$, $h_{10} = h_8 - (h_8 – h_9)\eta_T$	2162.2
4	$p_4 = p_2$, T_4	1217.8	11	$p_{11} = p_9$, $x_{11} = 0$	173.9
5	$p_5 = p_1$, $s_5 = s_4$	471.1	12	$p_{12} = p_8$, $s_{12} = s_{11}$	181.9
6	$p_6 = p_5$, $h_6 = h_4 - (h_4 – h_5)\eta_T$	545.8	13	$p_{13} = p_{12}$, $h_{13} = h_{11} + (h_{12} – h_{11})/\eta_P$	183.9
7	$p_7 = p_6$, T_7	103.0			

An energy balance on the adiabatic heat exchanger produces:

$$\dot{m}_1 (h_6 - h_7) \cong \dot{m}_8 (h_8 - h_{13})$$

$$\Rightarrow \dot{m}_1 = \frac{h_8 - h_{13}}{h_6 - h_7} \dot{m}_8 = \frac{3138.2 - 183.9}{545.8 - 103.0} \dot{m}_8 = 6.673 \dot{m}_8$$

The net power output can be written as:

$$\dot{W}_{net} = \dot{W}_{T,I} + \dot{W}_{T,II} - \dot{W}_C - \dot{W}_P$$

$$= \dot{m}_1 (h_4 - h_6) + \dot{m}_8 (h_8 - h_{10}) - \dot{m}_1 (h_3 - h_1) - \dot{m}_8 (h_{13} - h_{11})$$

$$= 452.2 \dot{m}_1$$

Given the net output as 500 MW, the mass flow rate of air can be calculated as:

$$\dot{m}_1 = 500{,}000 / 452.2 = 1107\, kg/s$$

To obtain the thermal efficiency the external heat addition is evaluated:

$$\dot{Q}_{in} = \dot{m}_1 \left(h_4 - h_3\right) = 1107\left(1217.8 - 366.5\right) = 942.39\,MW$$

The thermal efficiency is:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{500}{942.4} = 53.1\%$$

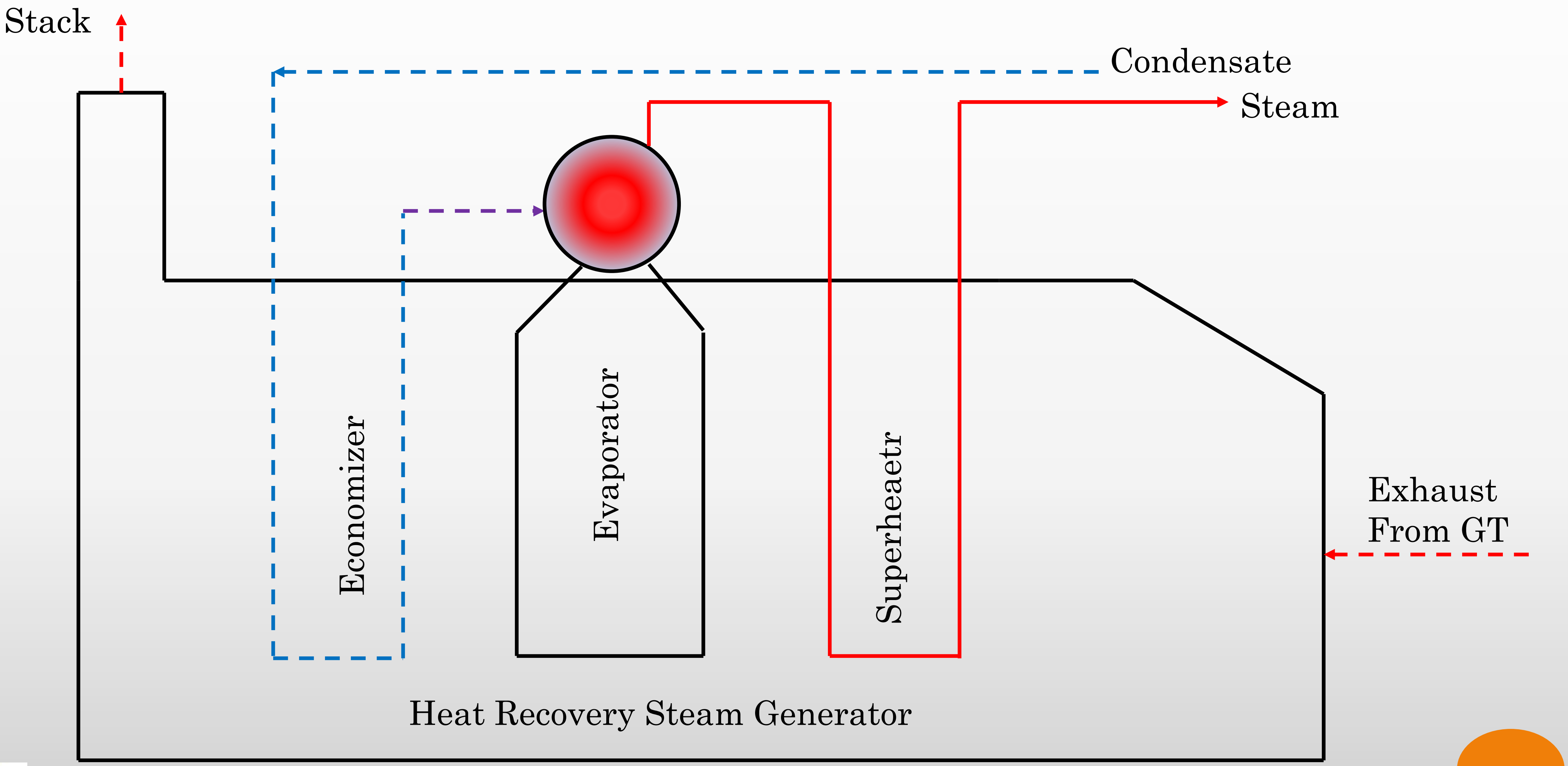
Heat Recovery Steam Generator

- The Topping Gas Turbine cycle is interlinked with the Bottoming Steam Power Plant through the Heat Recovery Steam Generator (HRSG).
- HRSG is an unique and important part of the GT-SPP combined cycle power plant.
- HRSG contains number of heat exchangers for feed water heating, water vaporization, steam superheating, reheating, etc.
- Additionally, it may also contain supplementary firing system and arrangement for emission control.

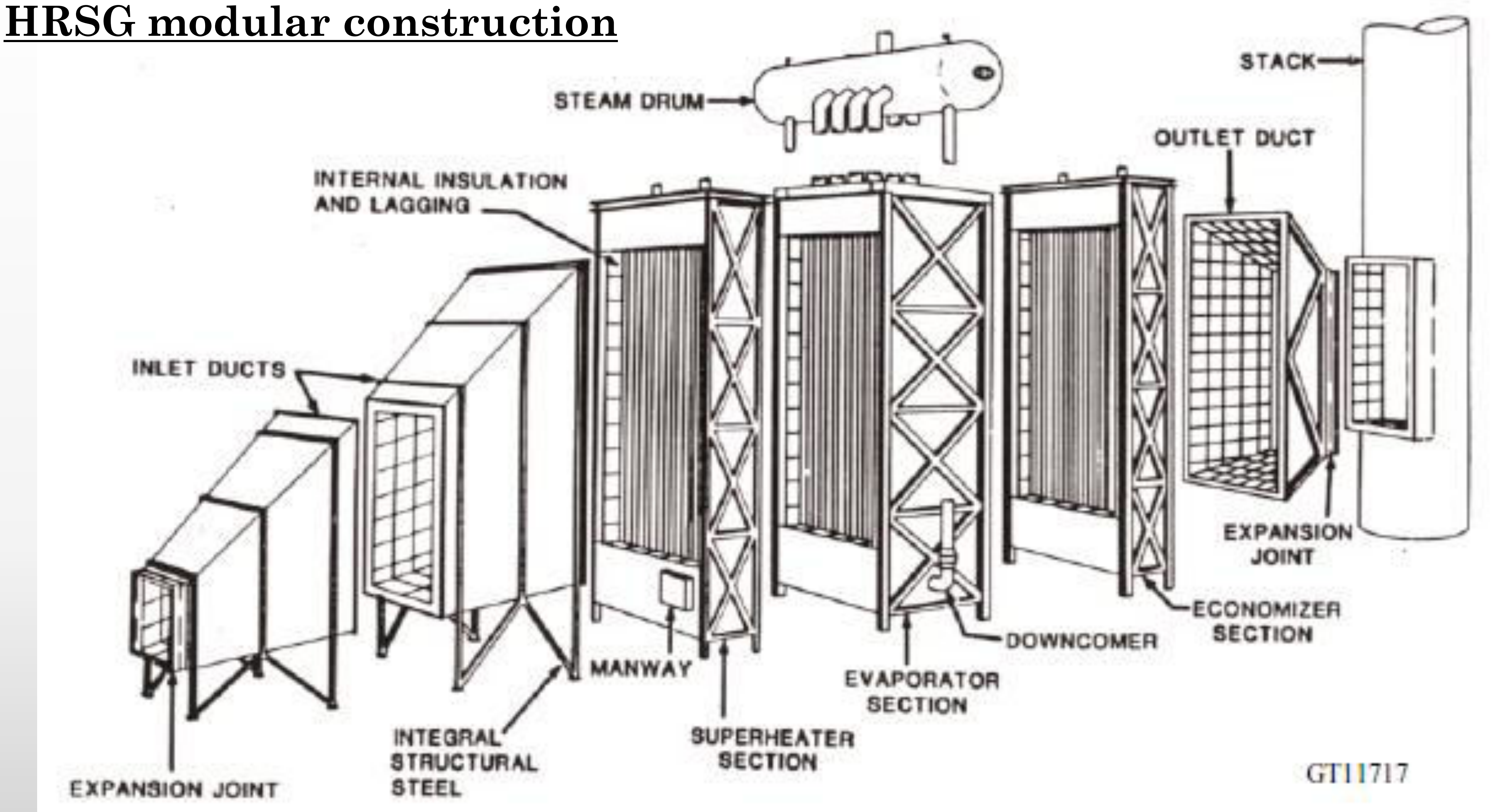
Classifications of HRSG

- Based on steam side operating pressure – single pressure, dual pressure and triple pressure
- Based on layout of equipments – horizontal and vertical
- Based on type of steam cycle – reheat or non-reheat
- Based on circulation – forced circulation and natural circulation
- Based on burning of fuels – unfired, exhaust fired and supplementary fired

Simplified representation of single pressure HRSG (natural circulation)

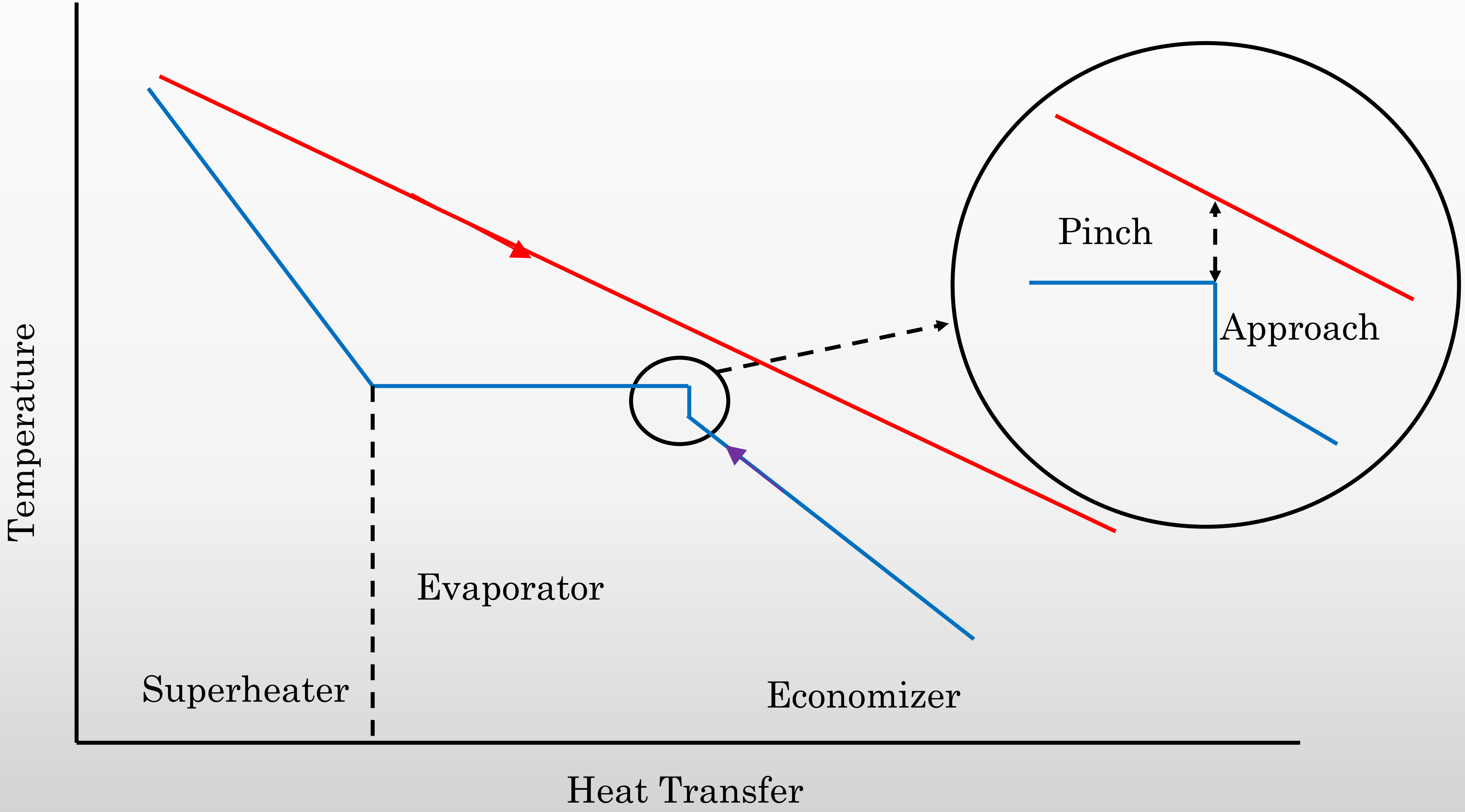


HRSG modular construction

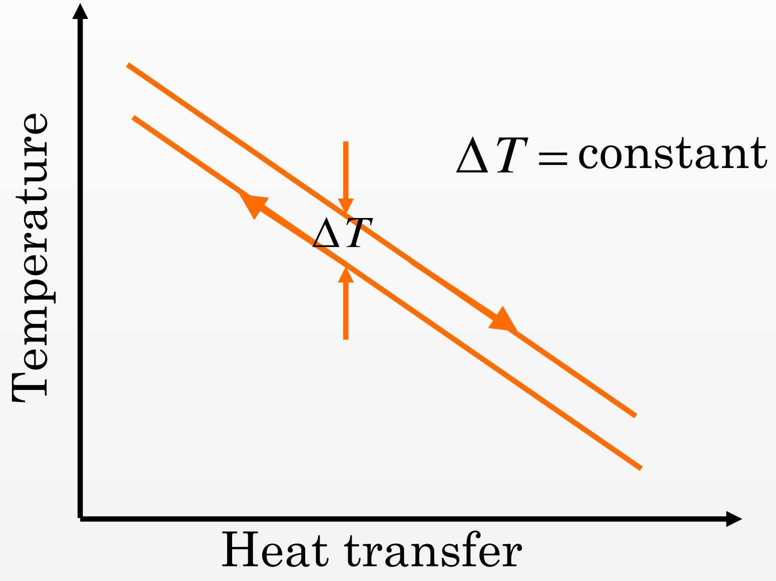


GE Power Systems GER-3574G

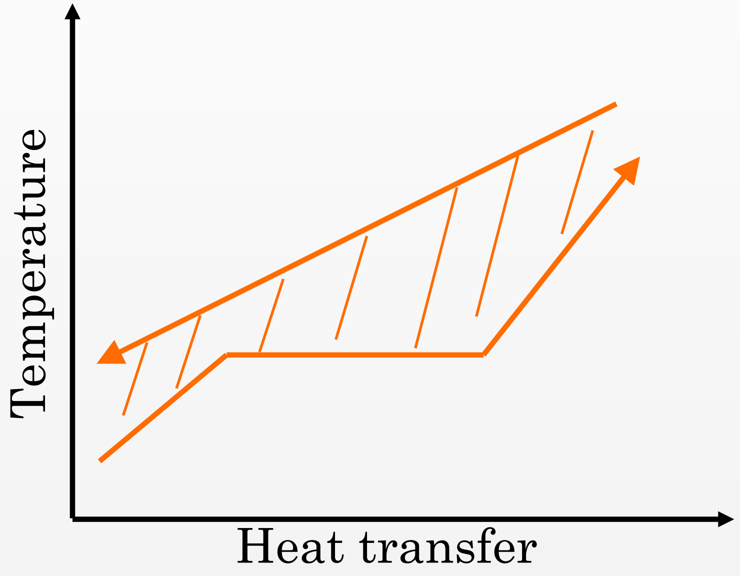
Temperature variation of flue gas and steam



Heat Recovery in HRSG



Ideal temperature profiles

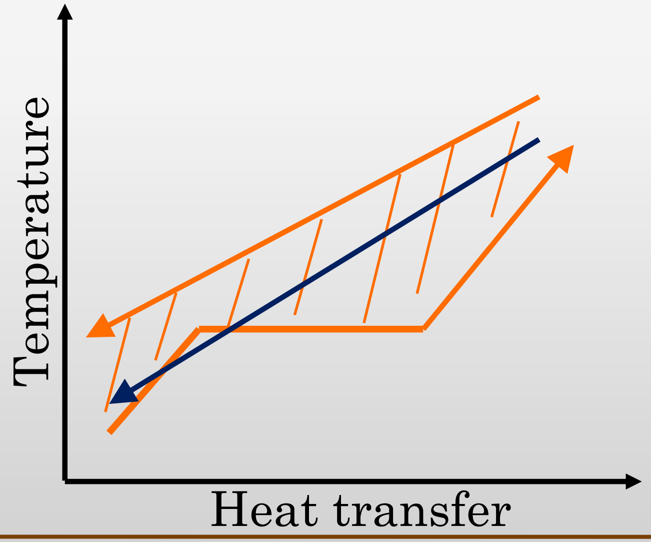


Actual temperature profiles

Waste heat recovery vs. initial cost and size of the equipment

Heat Recovery in HRSG

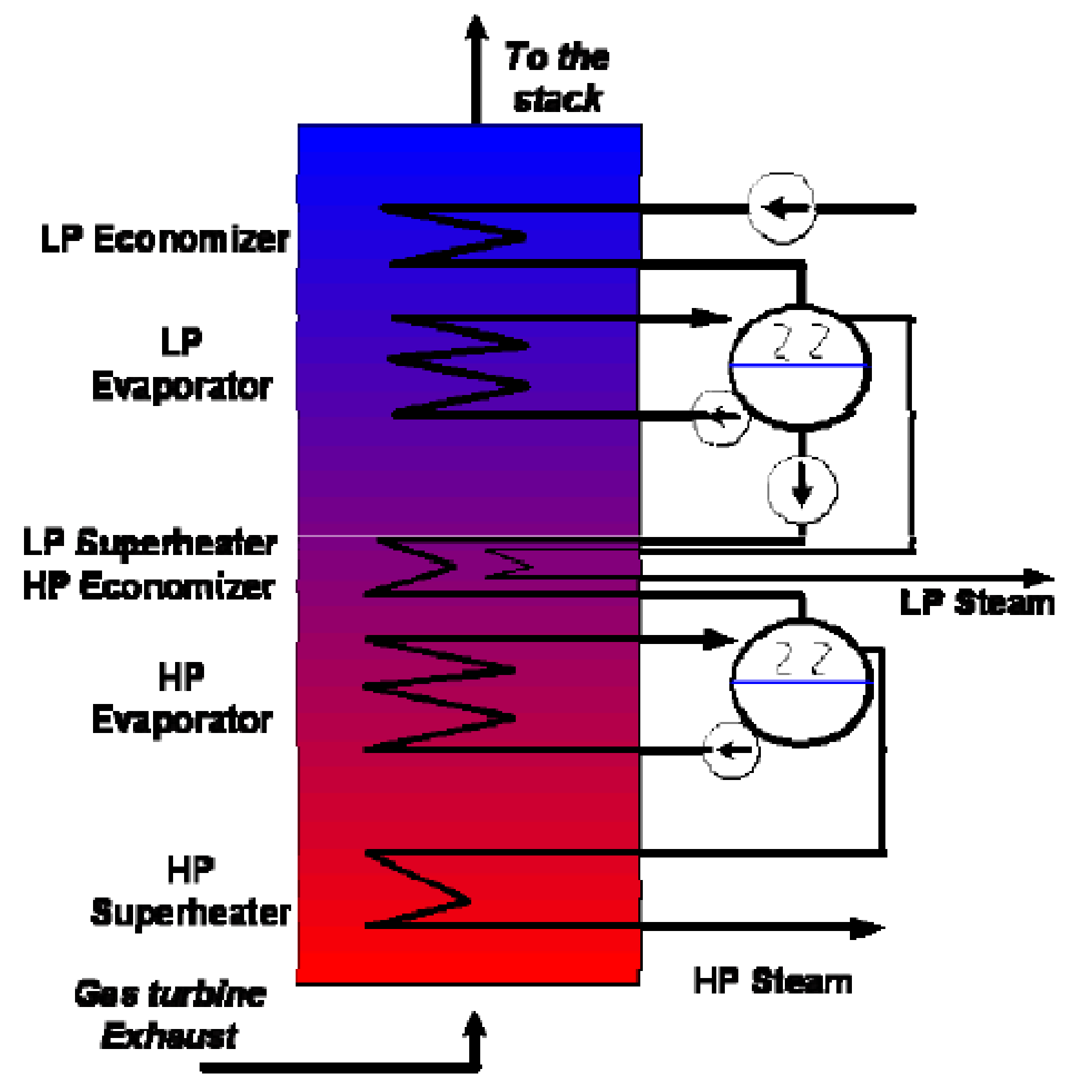
- Due to the shape of the heating curve of steam-water ΔT cannot be reduced to a low value
- ΔT is the maximum in the evaporator section and depends on the value of pinch temperature selected
- A finite value of pinch needs to be taken to avoid temperature cross-over
- Finite value of approach to be taken to avoid boiling in the economizer

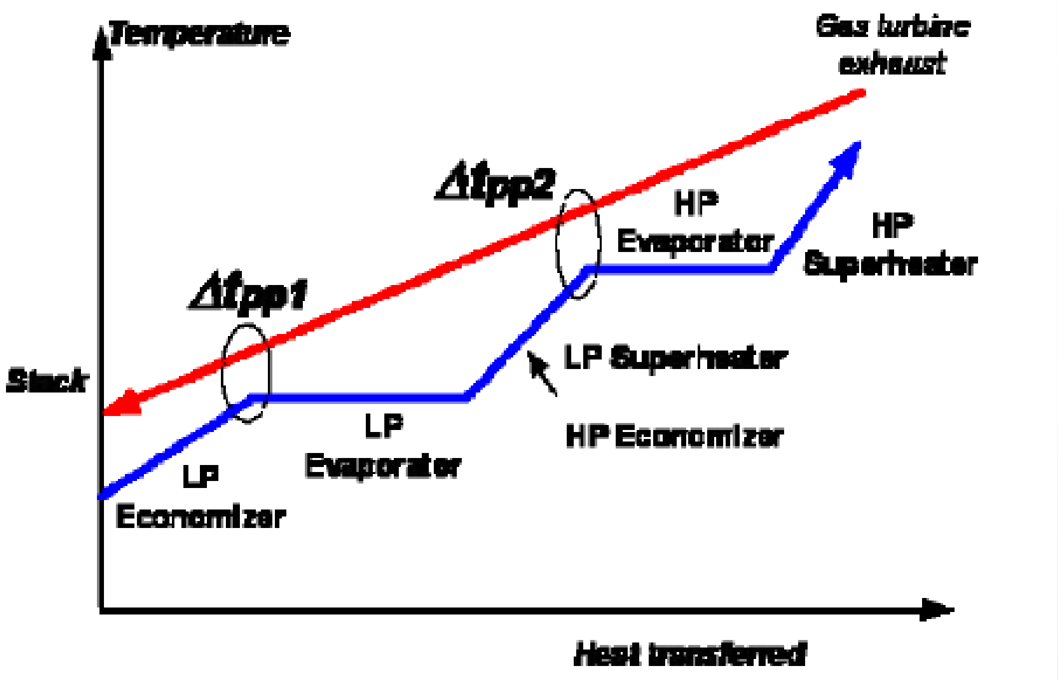


Methods for improving the efficiency of HRSG

- Multiple pressure steam generation
- Optimizing arrangement of heating surfaces
- Auxiliary firing
- Provision of secondary surfaces such as condensate heater, de-aerator or heat exchanger
- Reduction of gas side resistance to heat transfer providing fins or suitable designs
- Using low pinch and approach points

Multi pressure HRSG





Selective Catalytic Reactor (SCR) system for HRSG

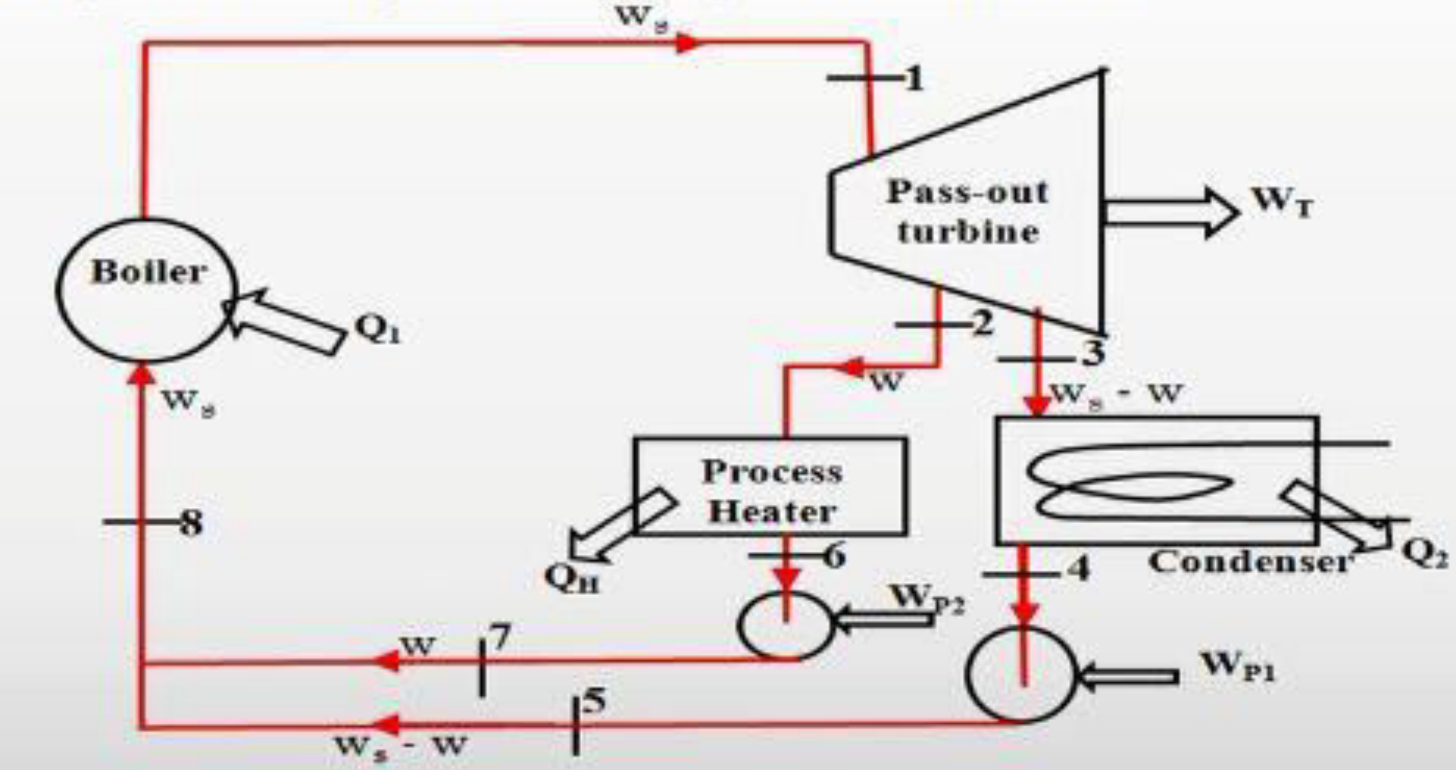
- Many of the HRSG has a SCR system to remove NO_x (NO, NO_2). Aqueous ammonia is used as the reducing agent.
- NO_3 reacts selectively with NO and NO_2

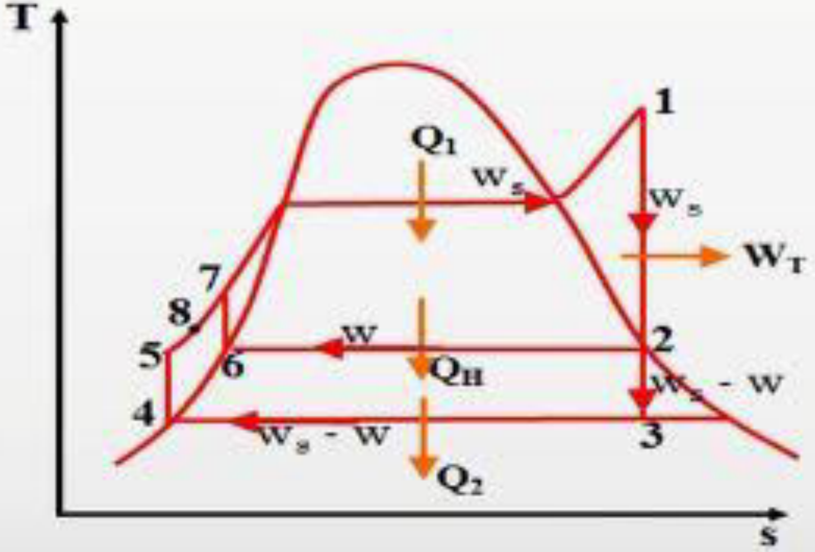
$$4NO + 4NH_3 + O_2 = 4N_2 + 6H_2O$$

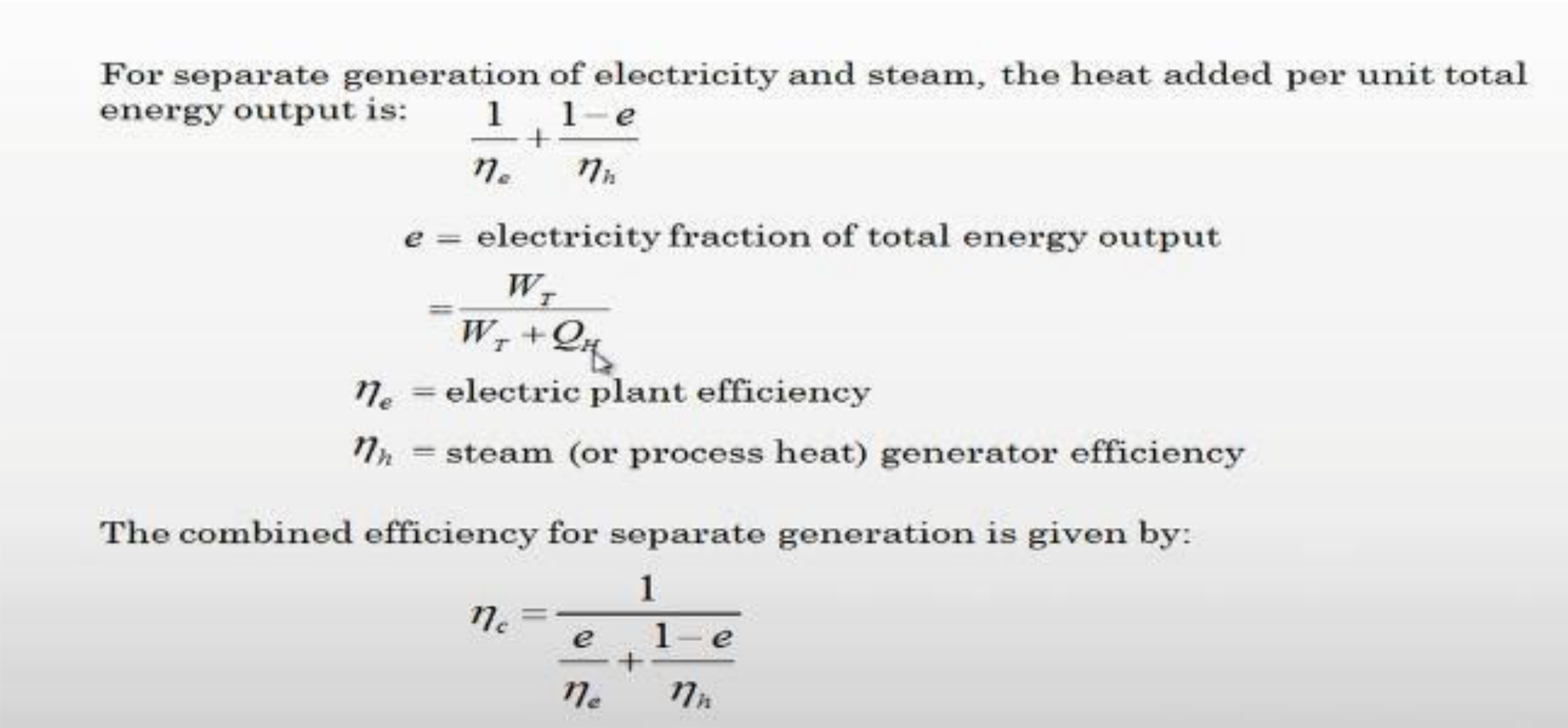
$$NO + NO_2 + 2NH_3 = 2N_2 + 3H_2O$$

- A catalyst bed made of compact homogeneous honeycomb is used. The substrate is a mixture of Titanium dioxide, Tungsten oxide and Vanadium pentoxide. Ammonia solution is injected. Best performance is obtained between 335 ºC to 24 ºC

Cogeneration plant with a pass-out turbine







For separate generation of electricity and steam, the heat added per unit total energy output is: $\frac{1}{\eta_e}+\frac{1-e}{\eta_h}$

$e =$ electricity fraction of total energy output

$$=\frac{W_T}{W_T+Q_H}$$

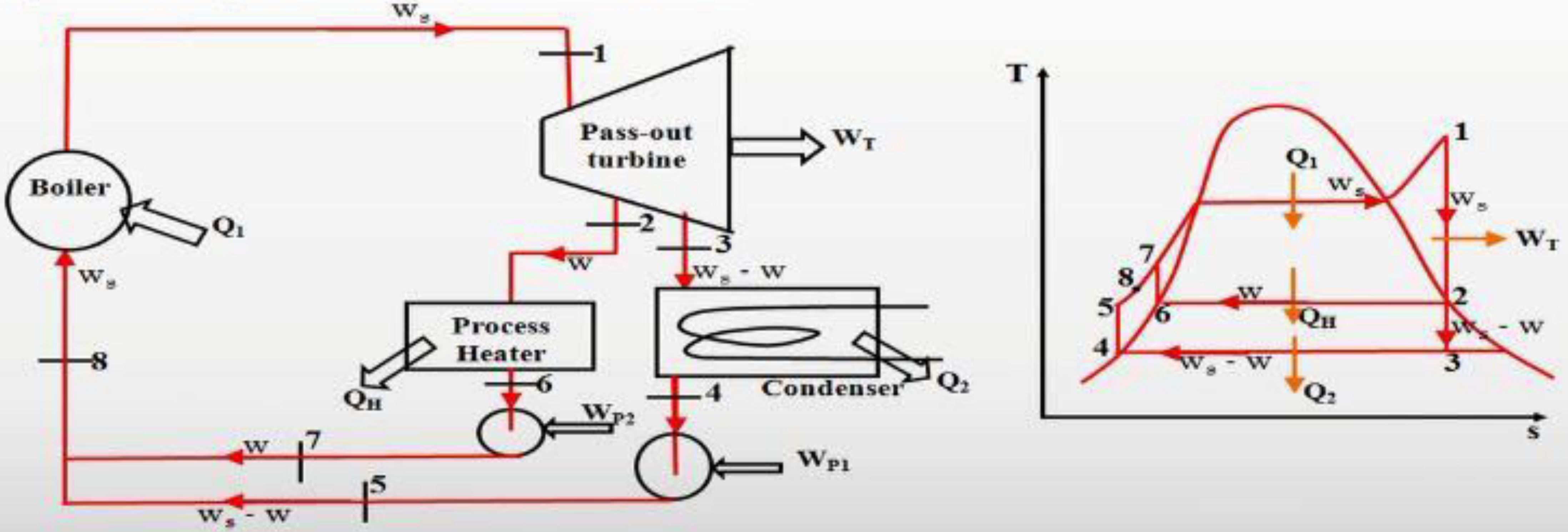
η_e = electric plant efficiency

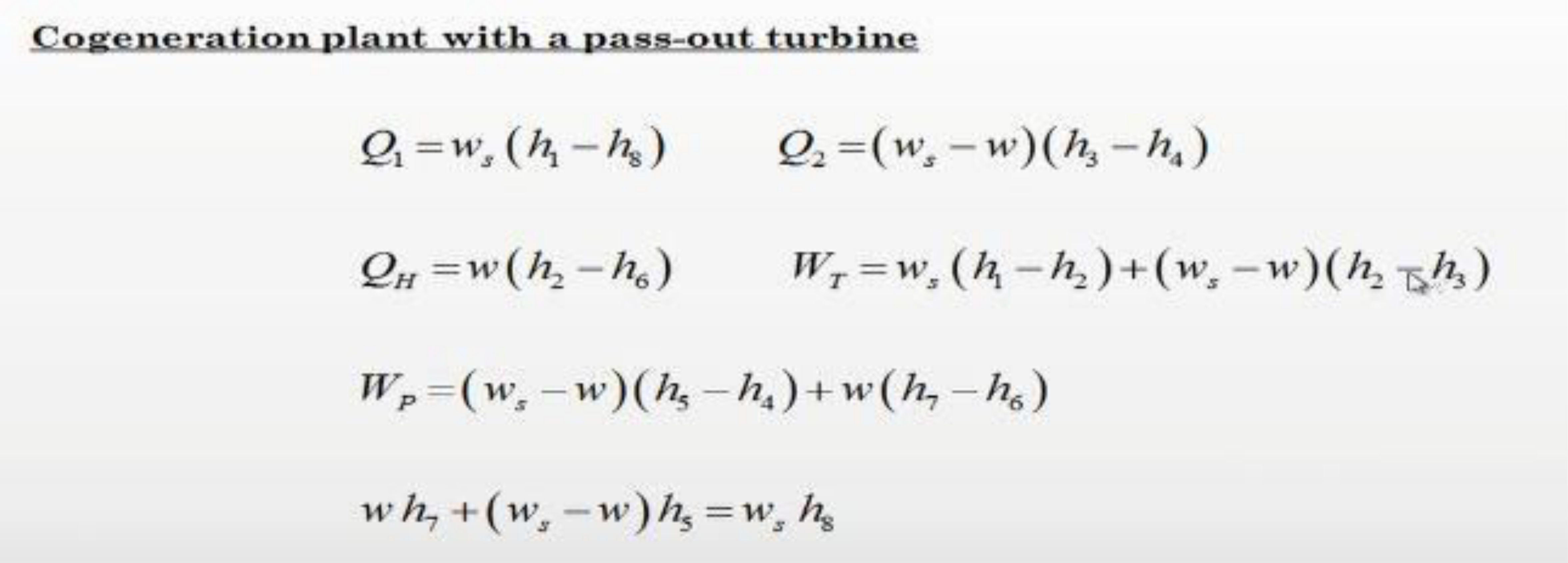
η_h = steam (or process heat) generator efficiency

The combined efficiency for separate generation is given by:

$$\eta_c=\frac{1}{\frac{e}{\eta_e}+\frac{1-e}{\eta_h}}$$

Cogeneration plant with a pass-out turbine





Cogeneration plant with a pass-out turbine

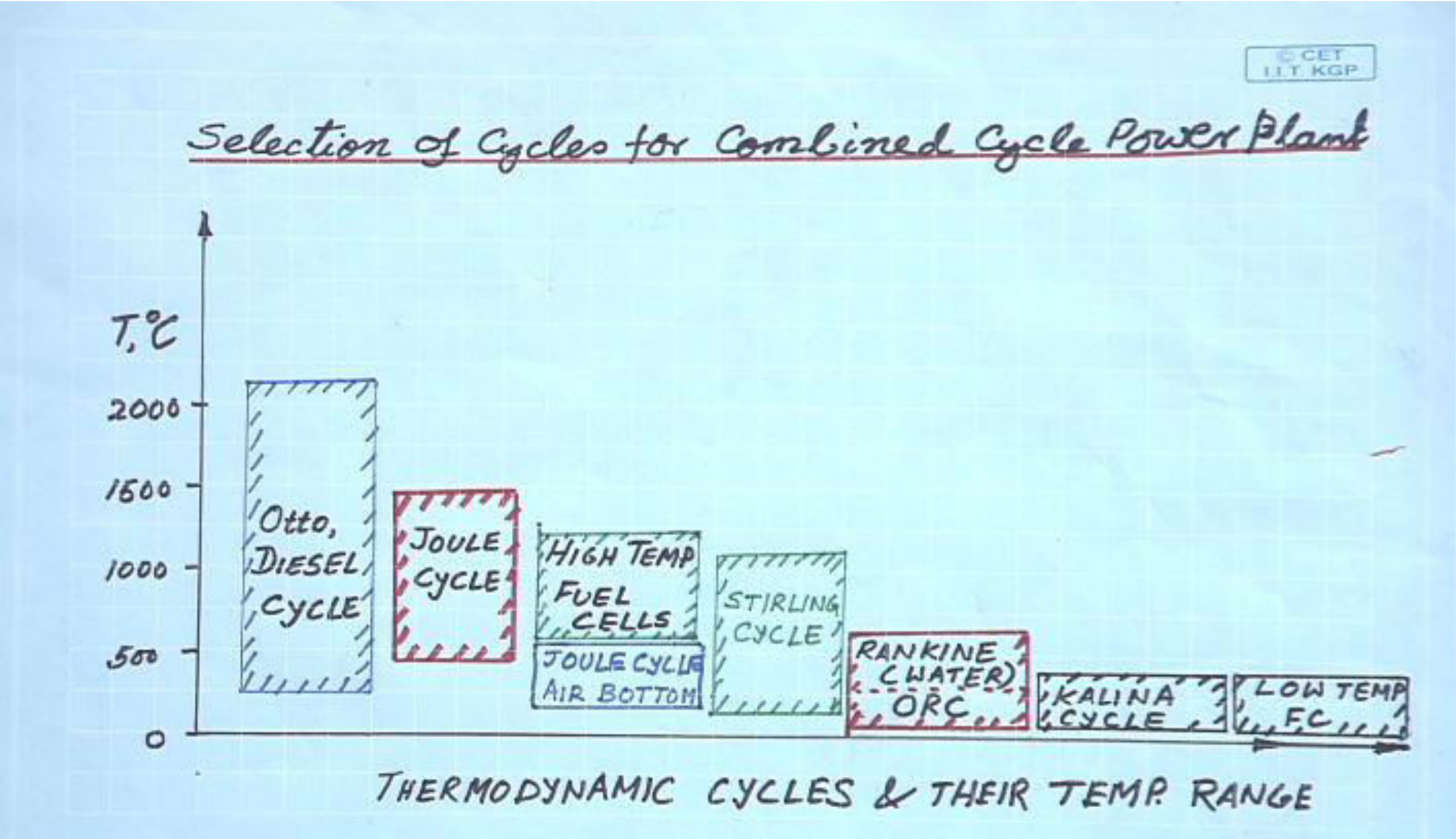
$$Q_1 = w_s(h_1 - h_8) \qquad Q_2 = (w_s - w)(h_3 - h_4)$$

$$Q_H = w(h_2 - h_6) \qquad W_T = w_s(h_1 - h_2) + (w_s - w)(h_2 - h_3)$$

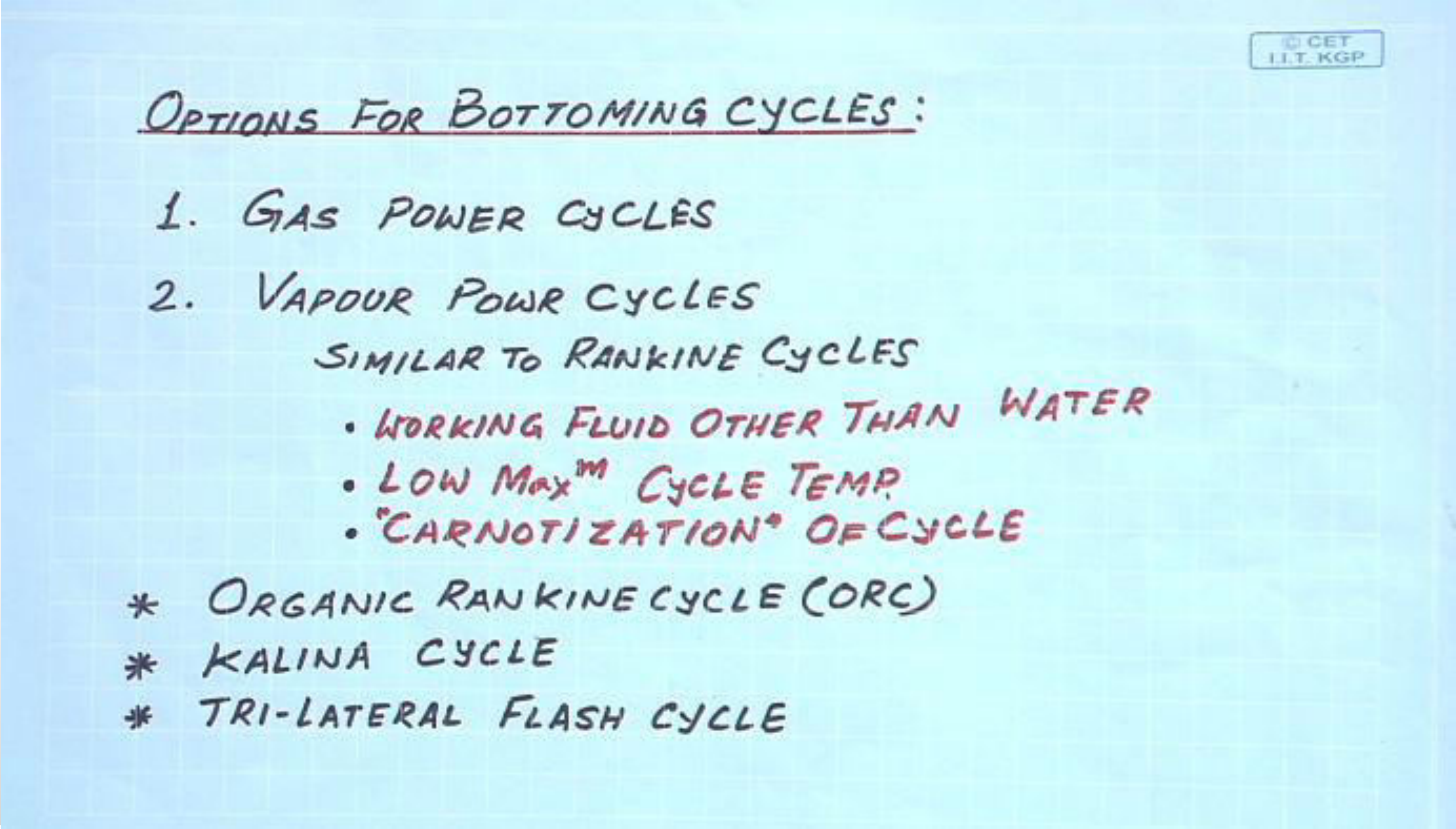
$$W_P = (w_s - w)(h_5 - h_4) + w(h_7 - h_6)$$

$$w\,h_7 + (w_s - w)\,h_5 = w_s\,h_8$$

Selection of Cycles for Combined Cycle Power Plant



THERMODYNAMIC CYCLES & THEIR TEMP. RANGE



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OPTIONS FOR BOTTOMING CYCLES :

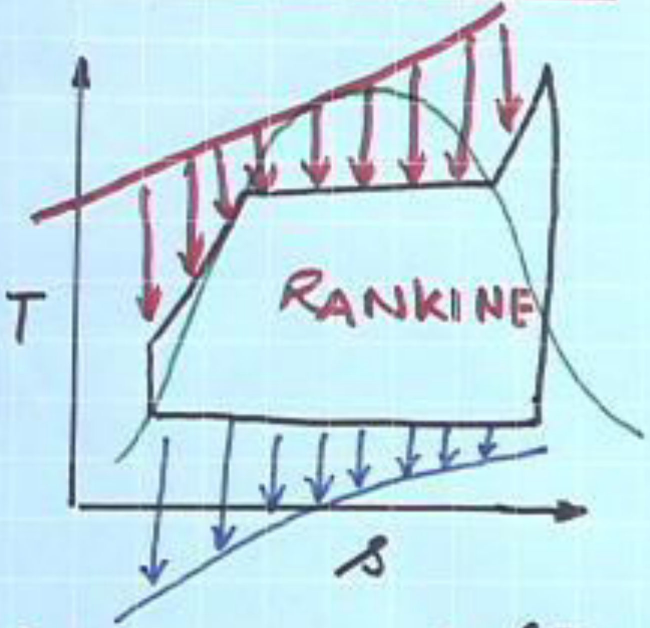
1. GAS POWER CYCLES
2. VAPOUR POWR CYCLES
   SIMILAR TO RANKINE CYCLES
   - WORKING FLUID OTHER THAN WATER
   - LOW MAX^{m} CYCLE TEMP.
   - "CARNOTIZATION" OF CYCLE

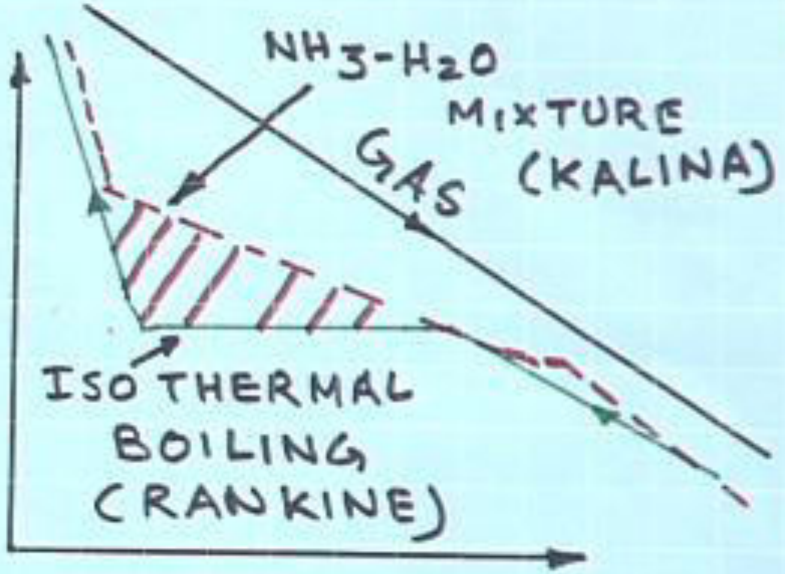
* ORGANIC RANKINE CYCLE (ORC)

* KALINA CYCLE

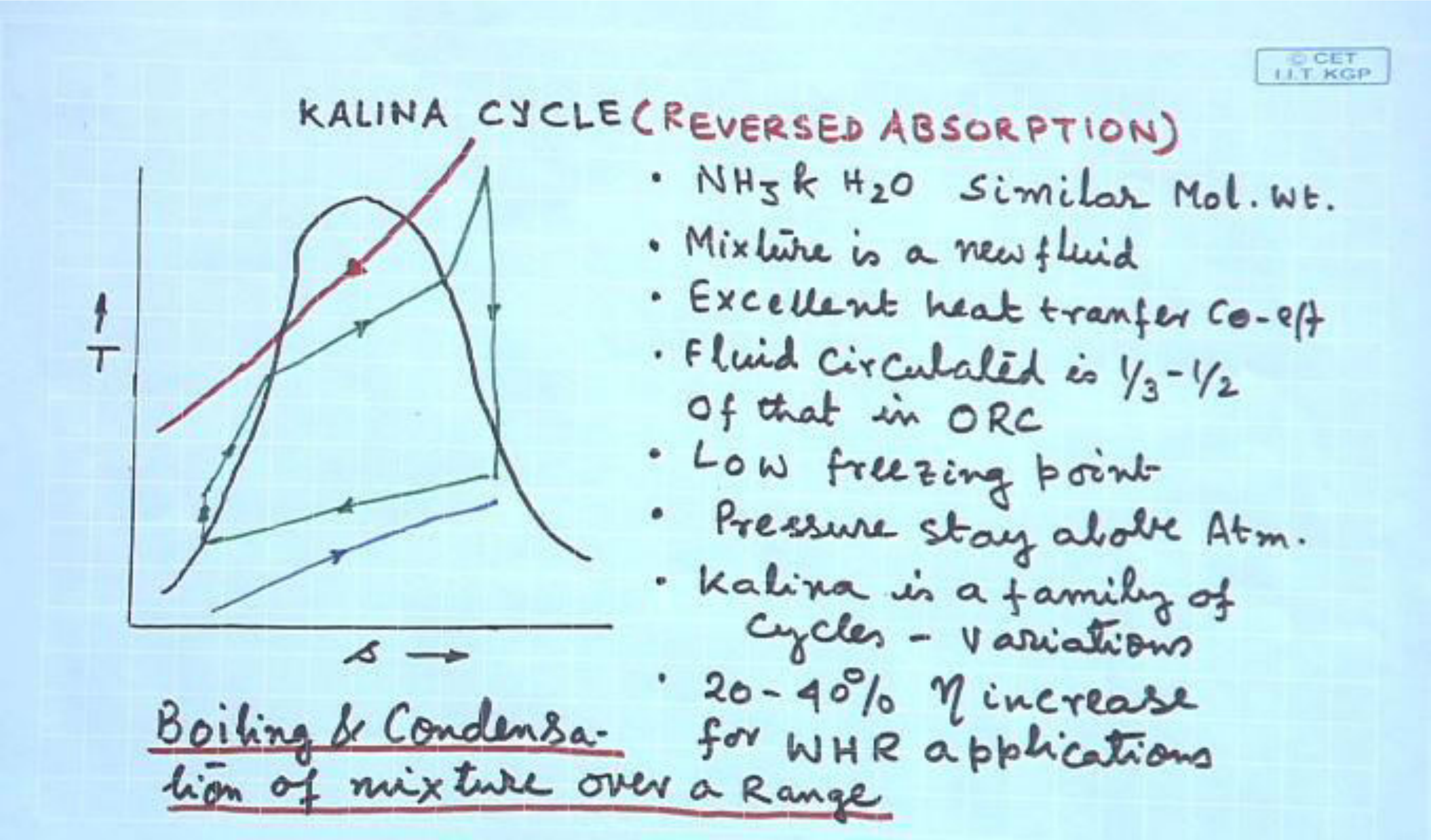
* TRI-LATERAL FLASH CYCLE

Kalina Cycle





- Divergence between the thermal behaviour of the source/sink and working fluid is a potential cause of irreversibility in cycle.
- Fluid mixture may reduce this.

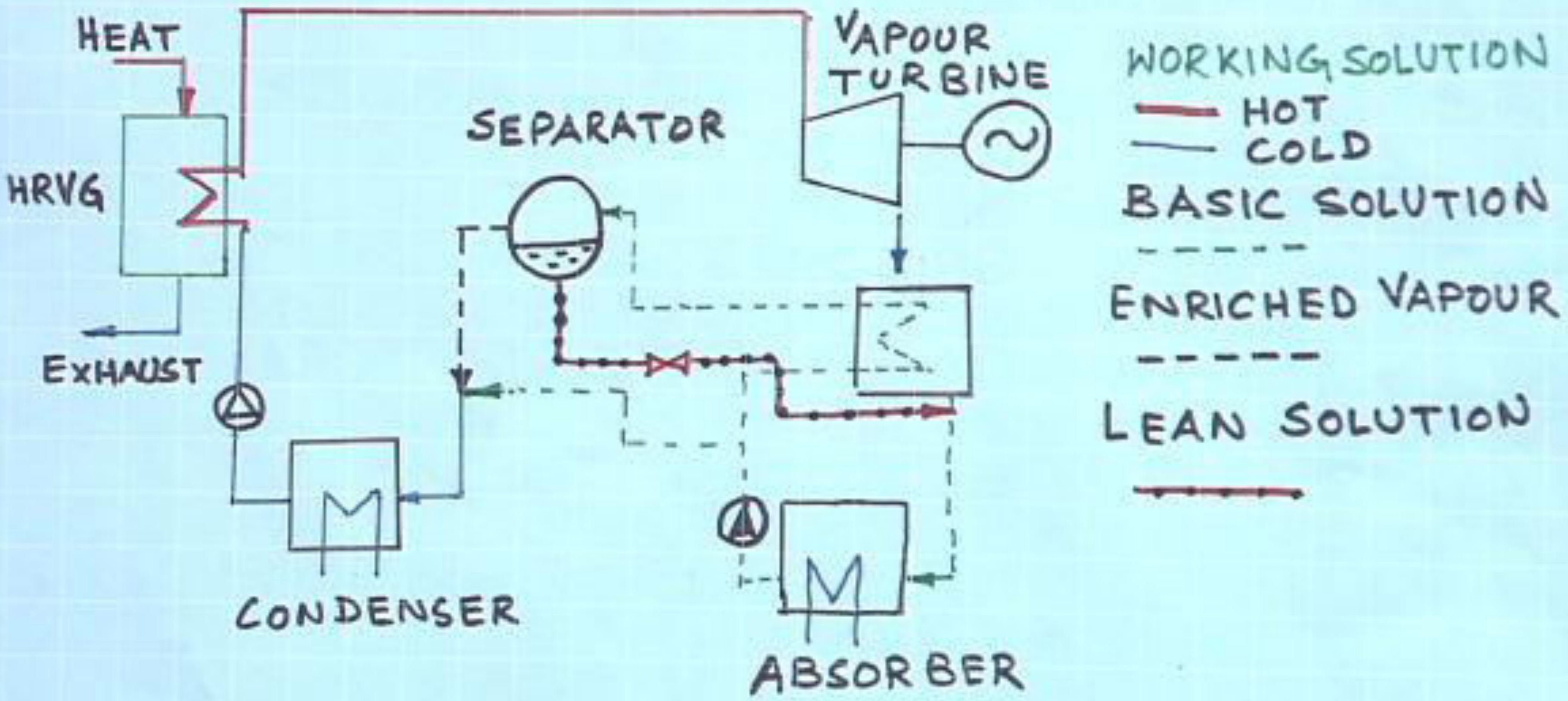


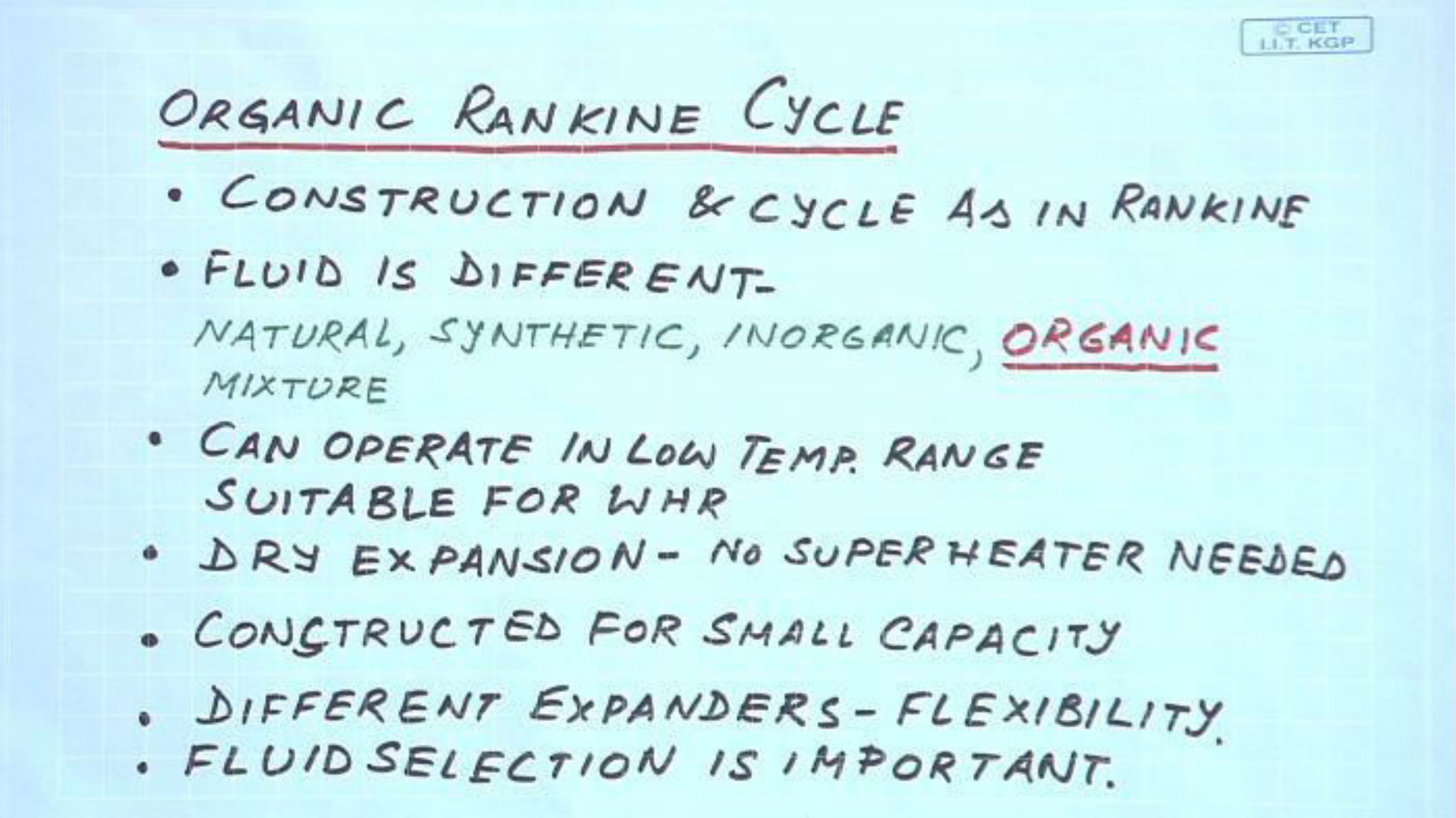
KALINA CYCLE (REVERSED ABSORPTION)

- NH_3 & H_2O similar Mol. Wt.
- Mixture is a new fluid
- Excellent heat tranfer co-eff
- Fluid circulated is 1/3 - 1/2 of that in ORC
- Low freezing point
- Pressure stay above Atm.
- Kalina is a family of cycles - variations
- 20-40% η increase for WHR applications

Boiling & Condensation of mixture over a Range

BASIC CALINA CYCLE





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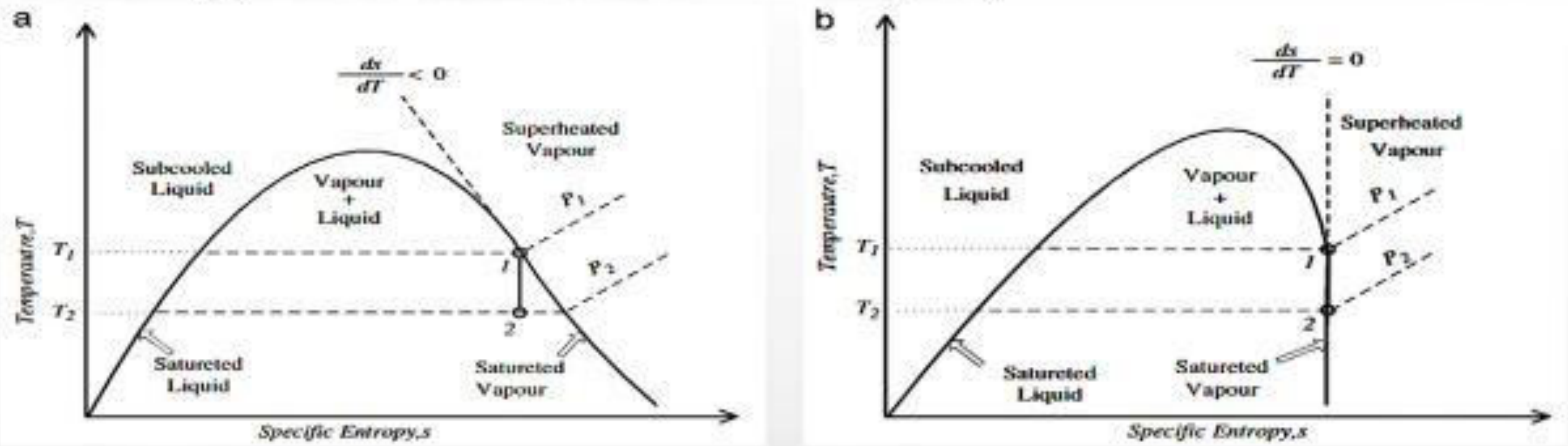
ORGANIC RANKINE CYCLE

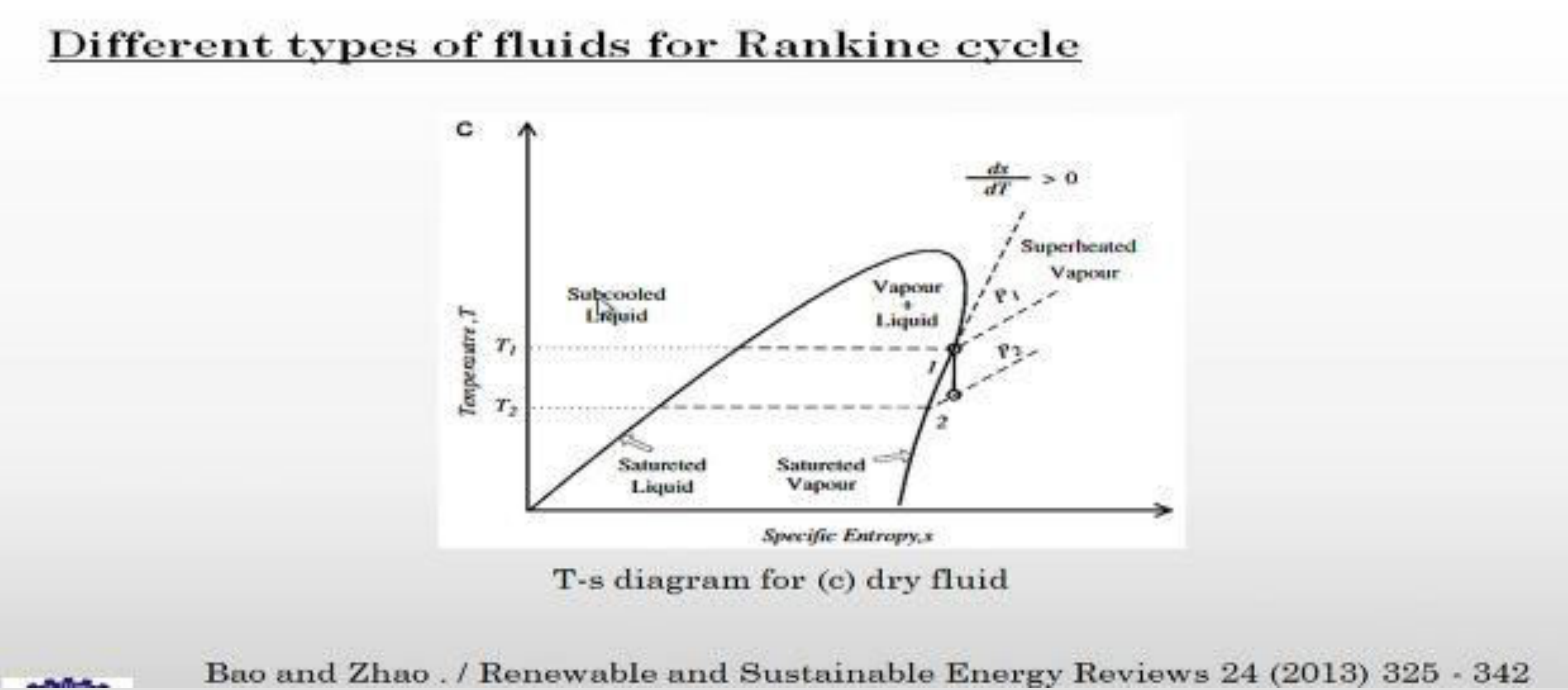
- CONSTRUCTION & CYCLE AS IN RANKINE
- FLUID IS DIFFERENT-
  NATURAL, SYNTHETIC, INORGANIC, ORGANIC
  MIXTURE
- CAN OPERATE IN LOW TEMP. RANGE
  SUITABLE FOR WHR
- DRY EXPANSION - NO SUPERHEATER NEEDED
- CONSTRUCTED FOR SMALL CAPACITY
- DIFFERENT EXPANDERS - FLEXIBILITY.
- FLUID SELECTION IS IMPORTANT.

Different types of fluids for Rankine cycle



T-s diagram for (a) wet and (b) isentropic fluids

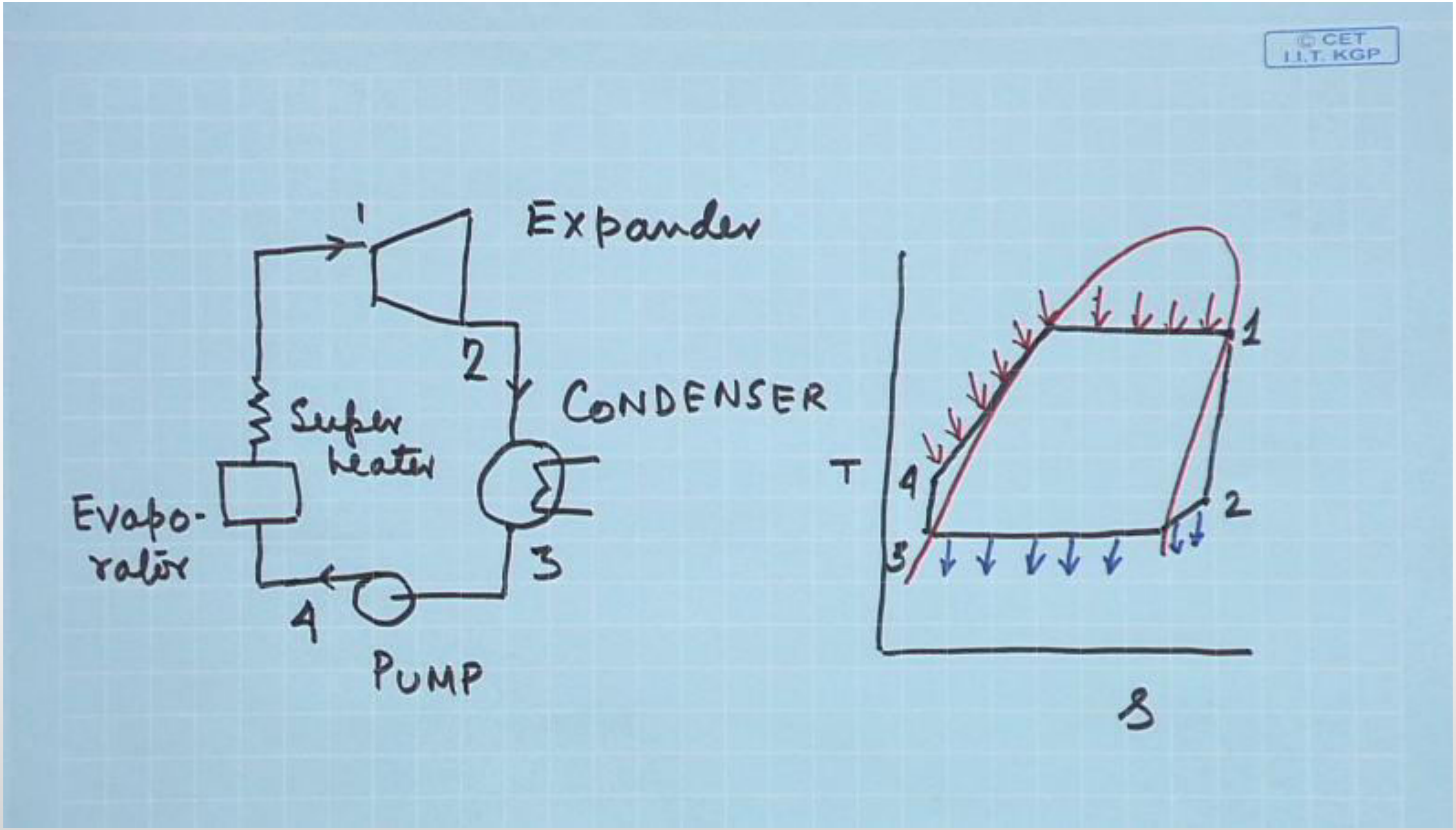
Bao and Zhao . / Renewable and Sustainable Energy Reviews 24 (2013) 325 - 342



Different types of fluids for Rankine cycle

T-s diagram for (c) dry fluid

Bao and Zhao . / Renewable and Sustainable Energy Reviews 24 (2013) 325 - 342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1
Expander
2
CONDENSER
3
Super heater
Evapo-rator
4
PUMP
T
1
4
2
3
s

Tri-Lateral Flash Cycle

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