



e NOTES

DJJ20063

THERMODYNAMICS

By :
Ts Mastura Binti Ibrahim
Rodziha Binti Sidek
Roshazul Nizam Bin Mohd Sani



**THE STEAM
POWER CYCLE**



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THERMODYNAMICS

The Steam Power Cycle

Ts Mastura Binti Ibrahim
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eNotes : The Steam Power Cycle
First edition 2024

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eNotes : The Steam Power Cycle is as general references and readings especially to lecturers and students of Polytechnics and colleges Malaysia community to apply best practices in method implementation online teaching and learning.

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Preface

A steam power plant is a facility designed to generate electricity through the use of steam as the primary working fluid. It operates based on the principles of thermodynamics, utilizing the conversion of heat energy into mechanical work and subsequently into electrical energy. The primary components of a steam power plant include a boiler, a turbine, a condenser, and a generator.

The content presented here covers the key stages of the steam cycle, from the generation of steam in boilers to its conversion into mechanical work through turbines and its condensation back into water. Special attention is given to the thermodynamic principles governing these processes, as well as real-world applications and advancements that continue to drive improvements in efficiency and environmental sustainability.



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1 CONCEPT OF SECOND LAW OF THERMODYNAMICS



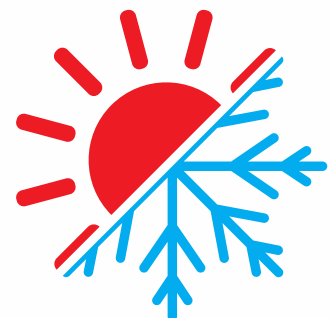
DEFINITION

Although the net heat supplied in a cycle is equal to the net work done, the gross heat supplied must be **GREATER THAN** the work done; some heat must always be rejected by the system.

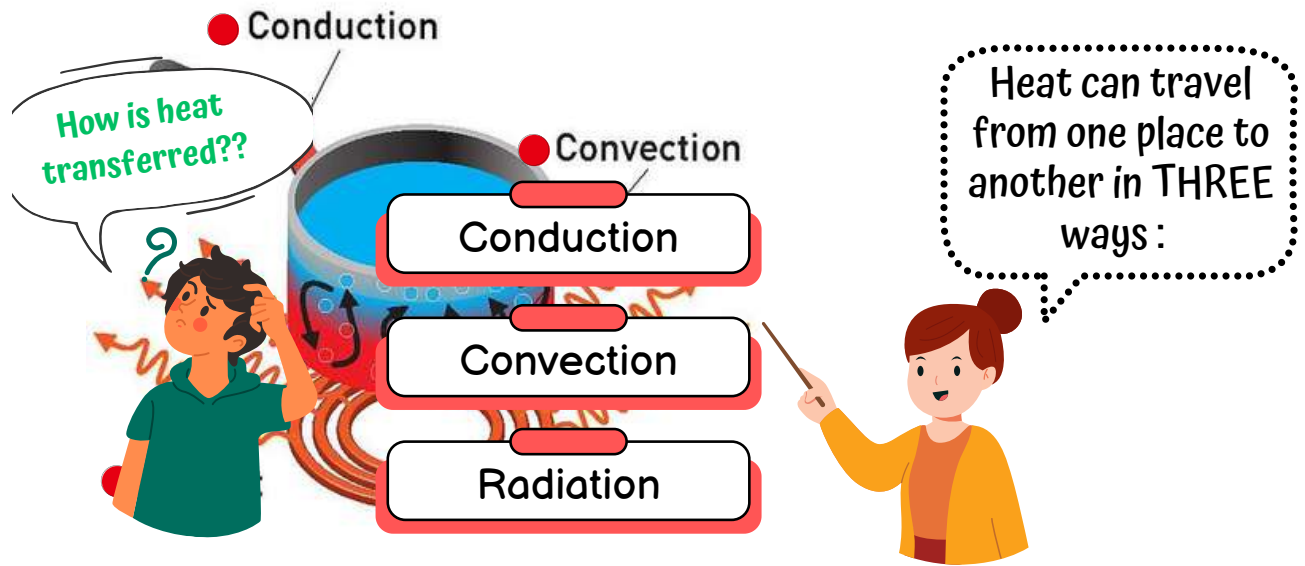
$$\text{Equation : } Q_1 - Q_2 = W$$

PRINCIPLES HEAT TRANSFER

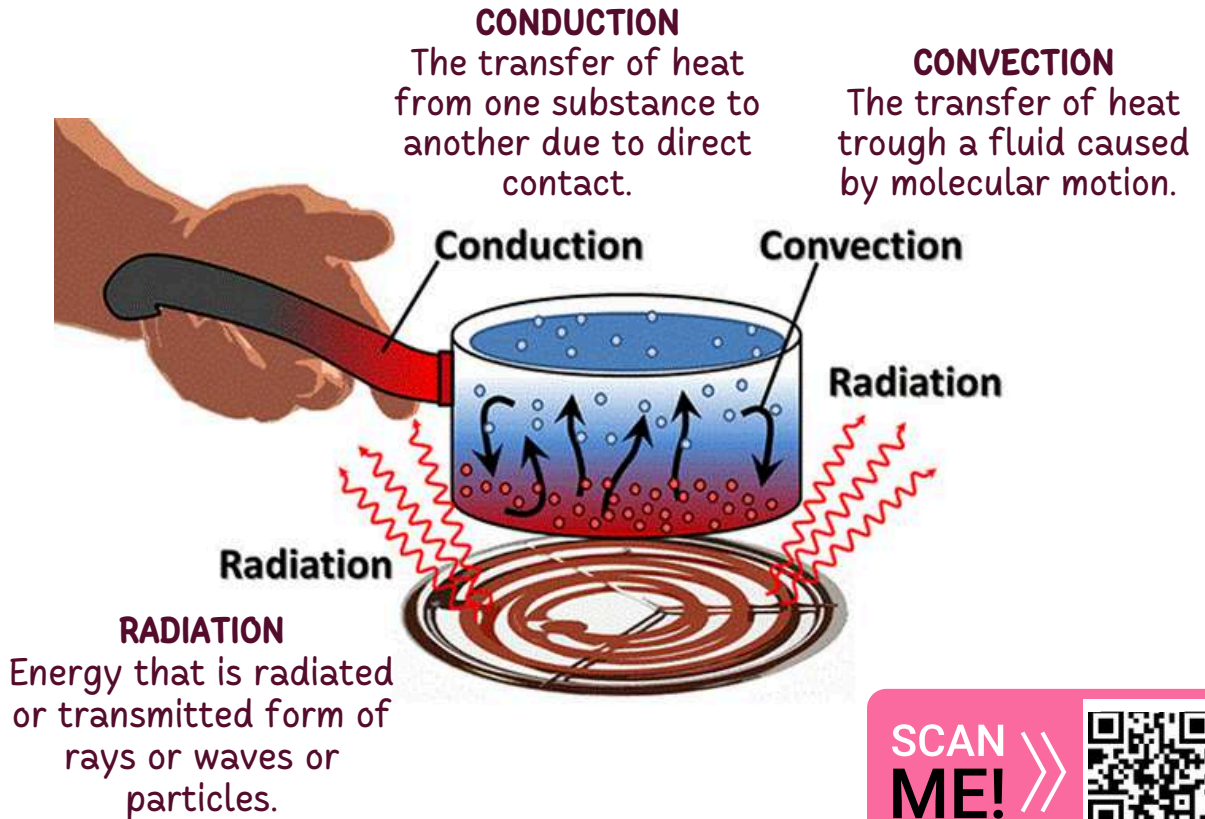
The movement of heat across the border of the system due to a difference in temperature between the system and its surroundings



PRINCIPLES OF HEAT TRANSFER



THREE TYPES OF HEAT TRANSFER



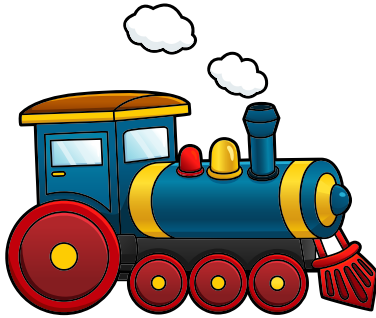
SCAN ME! >>>



Figure 1 : Types of Heat Transfer

2

PRINCIPLES OF HEAT ENGINE AND REVERSE OF HEAT ENGINE



HEAT ENGINE

A heat engine is a device that converts heat to work. It takes heat from a reservoir then does some work like moving a piston, lifting weight etc and finally discharges some heat energy into the sink.

CHARACTERISTIC OF HEAT ENGINE

- Receives heat from a high-temperature source (solar, steam boiler and nuclear reactor)
- Convert part of that heat is transform to work (rotating shaft, gas turbine and steam turbine)
- Reject the remaining waste heat to a low temperature sink (river, lake, atmosphere)
- Operate in a cycle.

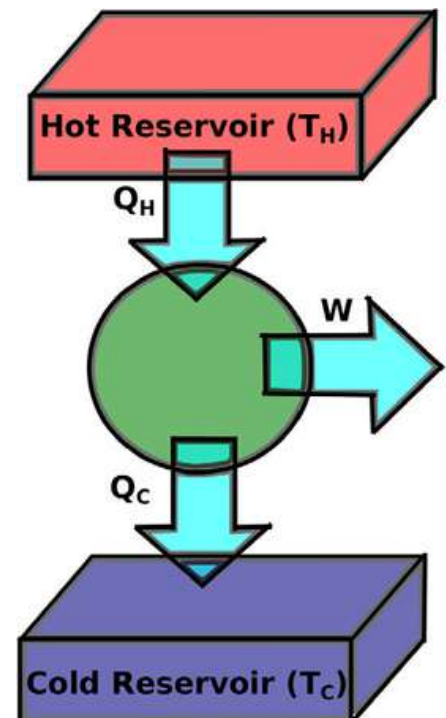


Figure.2 : Heat Engine

NOTES

Q_H - Heat supply from the source

Q_C - Heat rejected to the sink

W - The net Work Done

THERMAL EFFICIENCY OF HEAT ENGINE



Thermal Efficiency of heat engine is defined as a ratio of the net work done in the cycle to heat supplied in the cycle.

By the first law, in a complete cycle,
Net heat supplied = Net work done

$$\Sigma Q = \Sigma W \Rightarrow Q_1 - Q_2 = W \quad (1)$$

By the second law, the gross heat supplied must be greater than the net work done,
i.e. $Q_1 > W$

Thermal Efficiency of heat engine

$$\text{Thermal efficiency, } \eta = \frac{W}{Q_1} \quad (2)$$

Substituting in equation (i)

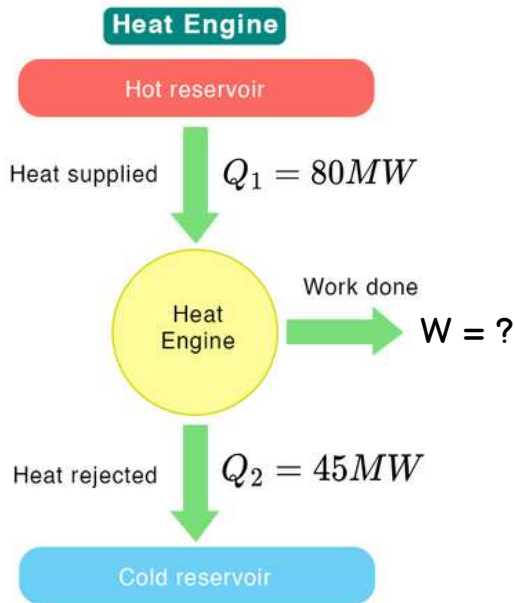
$$\eta = \frac{(Q_1 - Q_2)}{Q_1} \Rightarrow \eta = 1 - \left[\frac{Q_2}{Q_1} \right] \quad (3)$$

*The second law implies that the thermal efficiency of a heat engine must always be LESS than 100% [$Q_1 > W$].



Heat is transferred a heat engine from a furnace at a rate of 8MW. If the rate of waste heat rejection to a nearby river is 45 MW. Determine the net work done and the thermal efficiency for this heat engine.

Solution



Assumption :

Heat loss through the pipes and other component are negligible.

Analysis :

The given quantities can be expressed in rate from as :

$$Q_1 = 80MW$$

$$Q_2 = 45MW$$

From equation (1)

$$Q_1 - Q_2 = W \quad \Rightarrow \quad \begin{aligned} W &= Q_1 - Q_2 \\ &= 80 - 45 \\ &= 35MW \quad \checkmark \end{aligned}$$

From equation (ii) the thermal efficiency is :

$$\begin{aligned} \text{Thermal efficiency, } \eta &= \frac{W}{Q_1} = \frac{35MW}{80MW} \\ &= 0.4375 @ 43.75\% \quad \checkmark \end{aligned}$$

NOTES:

The heat engine converts 43.75% of heat it receives to work.

REVERSE OF HEAT ENGINE

Reverse engines convert thermal energy into mechanical work by transferring energy between a hot reservoir and a cold reservoir using a cyclical process. The reversed heat engine is called HEAT PUMP.

Heat engine operating in reversed direction as a refrigerator.

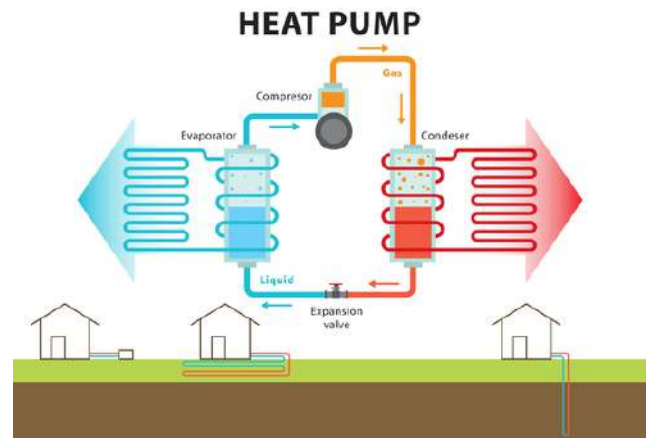
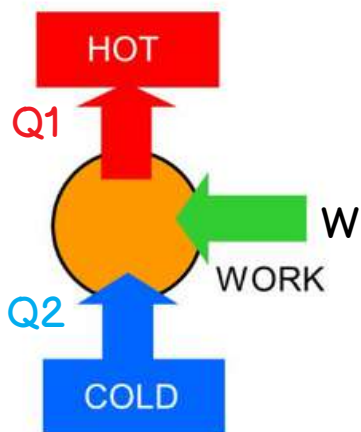


Figure 3 : Heat Pump

HEAT PUMP

Heat Pump is a device that extracts heat from one place and transfer it to another by using mechanical energy (example : air conditioner and refrigerator).



In the heat pump (or refrigerator) cycle :

Amount of heat, Q_2 is supplied from the **COLD** reservoir.

Amount of heat Q_1 is rejected to **HOT** reservoir.

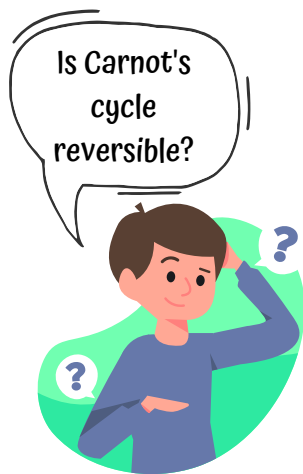
$$Q_1 = W + Q_2 \quad (4)$$

3

THE CARNOT CYCLE

A Carnot engine is a theoretical engine that operates on the Carnot cycle. Nicolas Leonard Sadi Carnot developed the basic model for this engine in 1824.

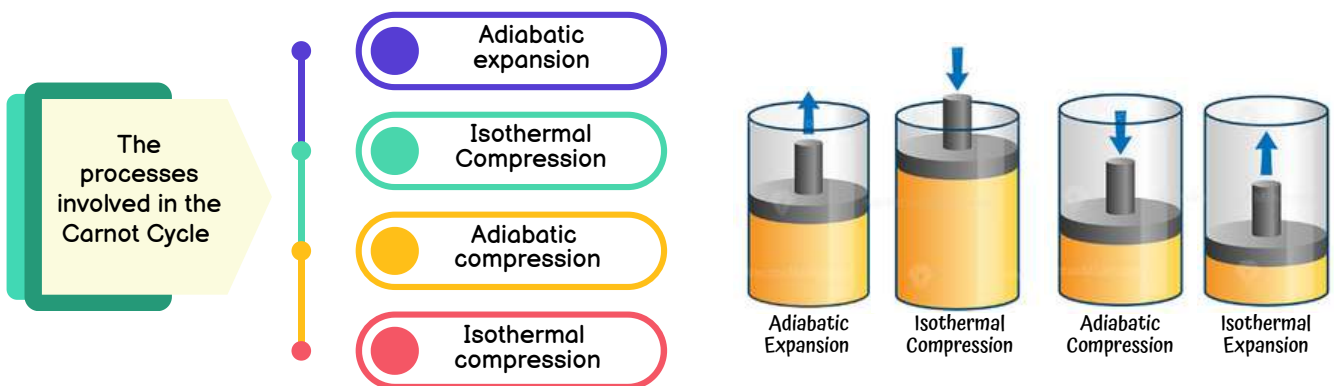
The Carnot engine is a theoretical thermodynamic cycle proposed by Leonard Carnot. It estimates the maximum possible efficiency that a heat engine during the conversion process of heat into work and, conversely, working between two reservoirs can possess.



The Carnot heat-engine cycle described is a totally reversible cycle.



During these operations, the **expansion** and **compression** of the substance can be done up to the desired point and back to the initial state.



SCAN ME! >>>



Figure 4 : Operation of Carnot Cycle

The cycle is most conveniently represented on a T-s diagram as shown in Figure 5 : Carnot Cycle Diagram

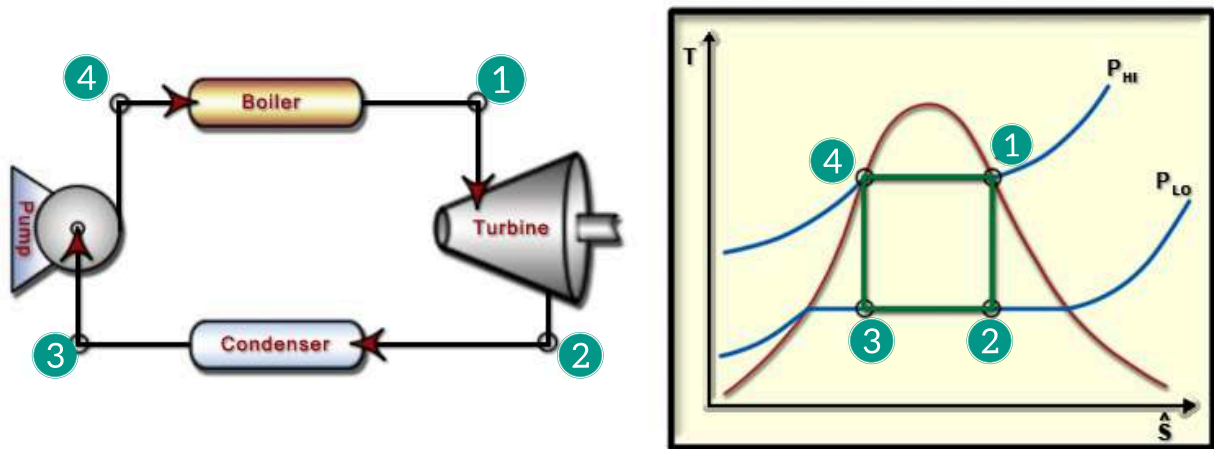
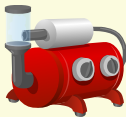


Figure 5 : Carnot Cycle Diagram

A brief summary of the essential features is as follows :

BOILER



The heat energy is supplied to the **BOILER** resulting in evaporation of the water, therefore the temperature remains constant.

$$Q_{41} = h_1 - h_4 \quad (5)$$

TURBINE



Isentropic expansion takes place in the **TURBINE** or engine.

$$W_{12} = h_1 - h_2 \quad (6)$$

CONDENSER



In the **CONDENSER**, condensation take place, therefore the temperature remain constant.

$$\text{Heat rejected in condenser} = h_2 - h_3 \quad (7)$$

COMPRESSOR



Isentropic compression of the wet steam in a **COMPRESSOR** returns the steam to its initial state.

$$\text{Work input to pump} = h_4 - h_3 \quad (8)$$

The cycle is most conveniently represented on a T-s diagram as shown in Figure 5 : Carnot Cycle Diagram

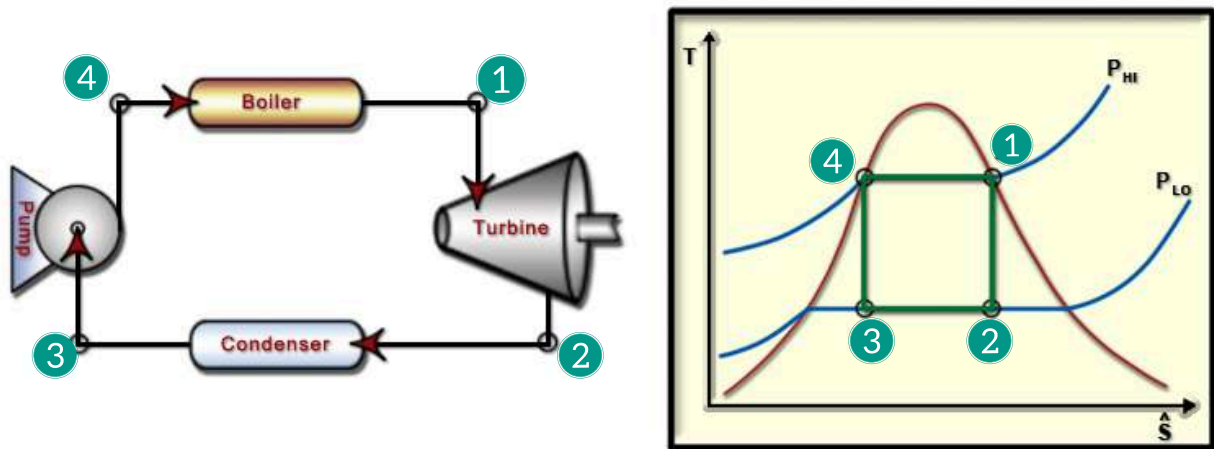


Figure 5 : Carnot Cycle Diagram

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The Thermal Efficiency of Carnot cycle

$$\eta_{carnot} = 1 - \frac{T_2}{T_1}$$

$$= \frac{\text{Net work output}}{\text{Heat supplied in the boiler}}$$

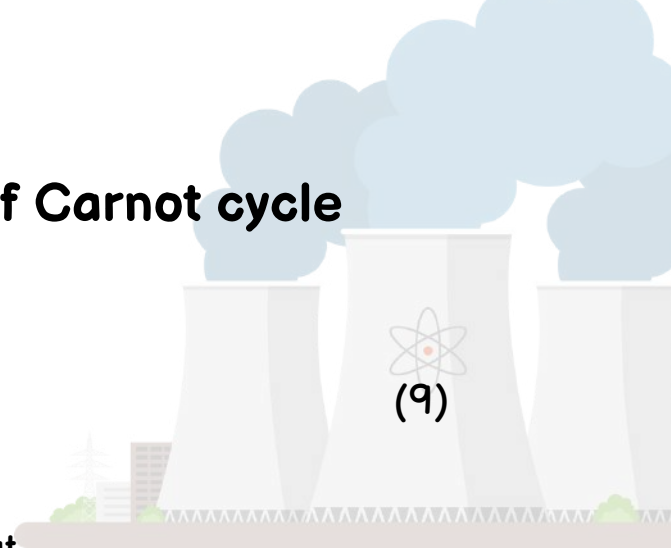
(10)

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

The Work Ratio for Carnot Cycle

$$\text{Work Ratio} = \frac{\text{Net Work}}{\text{Gross Work}} \quad (11)$$

$$\text{Work Ratio} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_2)} \quad (12)$$



Example

What is the highest possible theoretical efficiency of a Carnot cycle with a hot reservoir of steam at 200°C when the cooling water available from condenser is at 100°C?

SOLUTION

From equation (10) :

$$\begin{aligned}\eta_{carnot} &= 1 - \frac{T_2}{T_1} \\ &= 1 - \frac{10 + 273}{200 + 273} \\ &= 1 - \frac{283}{473} \\ &= 1 - 0.598 \\ &= \mathbf{0.402 \text{ or } 40.2\%}\end{aligned}$$

 Highest possible efficiency = 0.402 @ 40.2%

"let's" DO THIS EXERCISE

A steam power plant operates between a boiler pressure of 42 bar and a condenser pressure of 0.035 bar. Calculate for these limits the cycle efficiency and the work ratio for a Carnot cycle using wet steam.

A Carnot cycle is shown in the figure 6 given :

T_1 saturation temperature at 42 bar
 $= 253.2 + 273 = 526.2 \text{ K}$

T_2 saturation temperature at 0.035 bar
 $= 26.7 + 273 = 299.7 \text{ K}$

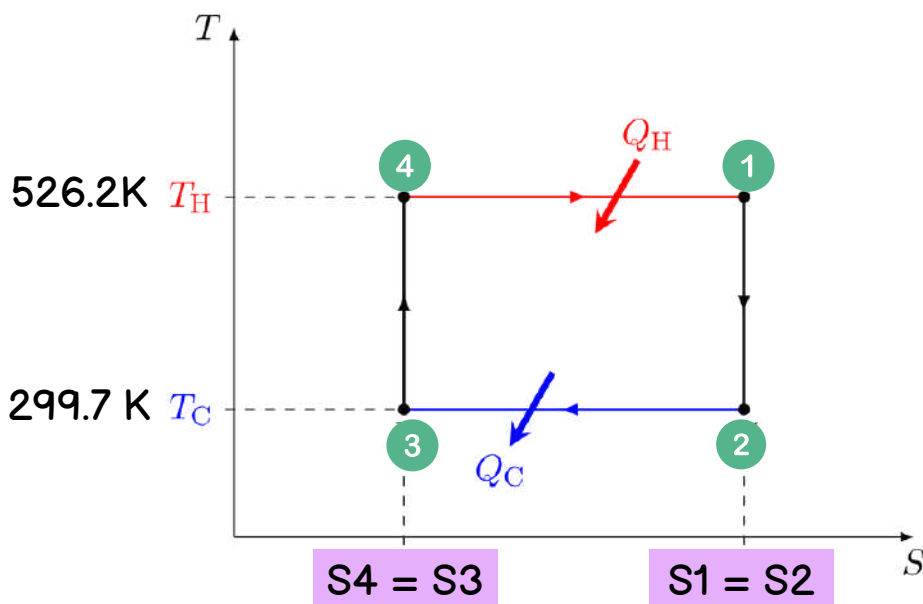


Figure 6 : T-s Diagram (Carnot Cycle)

1 Calculate the these limits the **cycle efficiency**

From equation (10) :

$$\begin{aligned}\eta_{carnot} &= \frac{T_1 - T_2}{T_1} \\ &= \frac{526.2 - 299.7}{526.2} \\ &= 0.432 \text{ or } 43.2\% \quad \checkmark\end{aligned}$$

2 The work ratio

$$\text{Work Ratio} = \frac{\text{Net Work}}{\text{Gross Work}}$$

STEPS TO FIND THE **WORK RATIO**

1 Find Heat Supplied

BOILER



Heat Supplied, $Q = h_1 - h_4 = h_{fg}$ at 42 bar
 $= 1698 \text{ kJ/kg} \quad \checkmark$

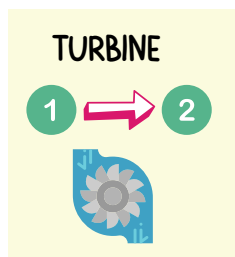


2 Find the net work

$$\eta_{carnot} = \frac{\text{Net work output}}{\text{Heat supplied in the boiler}}$$
$$= \frac{W_{net}}{Q_{in}} = 0.432$$

$$W = 734 \text{ kJ/kg} \quad \checkmark$$

3 Find the gross work



To find the gross work of the expansion process it is necessary to calculate h_2 , using the fact that $s_2 = s_1$.

From Steam Tables,

$$h_1 = 2800 \text{ kJ/kg and}$$
$$s_1 = s_2 = 6.049 \text{ kJ/kg K}$$



How to find
the Gross
Work??

Steps to find the gross work



1 Find dryness fraction

From the equation :

$$S_2 = 6.049 = S_{sf2} = 0.391 + x_2 8.13$$

$$x_2 = \frac{6.049 \times 0.391}{8.13}$$
$$= 0.696 \quad \checkmark$$

2 Find h_2

$$h_2 = h_{fg} + x_2 h_{fg2}$$
$$= 112 + (0.696 \times 2438)$$
$$= 1808 \text{ kJ/kg} \quad \checkmark$$

3 Find Gross Work

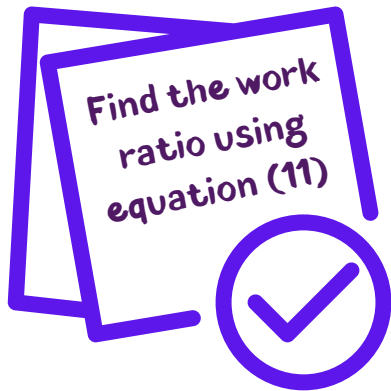
Hence, from equation (6) : The gross work is

$$W_{12} = (h_1 - h_2)$$
$$= (2800 - 1808)$$
$$= 992 \text{ kJ/kg} \quad \checkmark$$

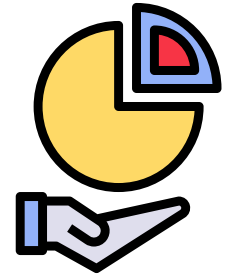
The gross work in
Turbine steam



4 Find the work ratio



$$\begin{aligned}\text{Work Ratio} &= \frac{\text{Net Work}}{\text{Gross Work}} \\ &= \frac{734}{992} \\ &= 0.739 \quad \checkmark\end{aligned}$$



Well!
done!

4

THE RANKINE CYCLE

The Rankine cycle is an idealized thermodynamic cycle describing the process by which certain heat engines, such as steam turbines or reciprocating steam engines, allow mechanical work to be extracted from a fluid as it moves between a heat source and heat sink.



The steam Rankine cycle is one of the highest utilized types of thermodynamic cycles for electricity production in the world. The steam power stations run on Rankine cycles using steam as a working fluid. The simple ideal Rankine cycle is in fact the most basic steam power cycle.

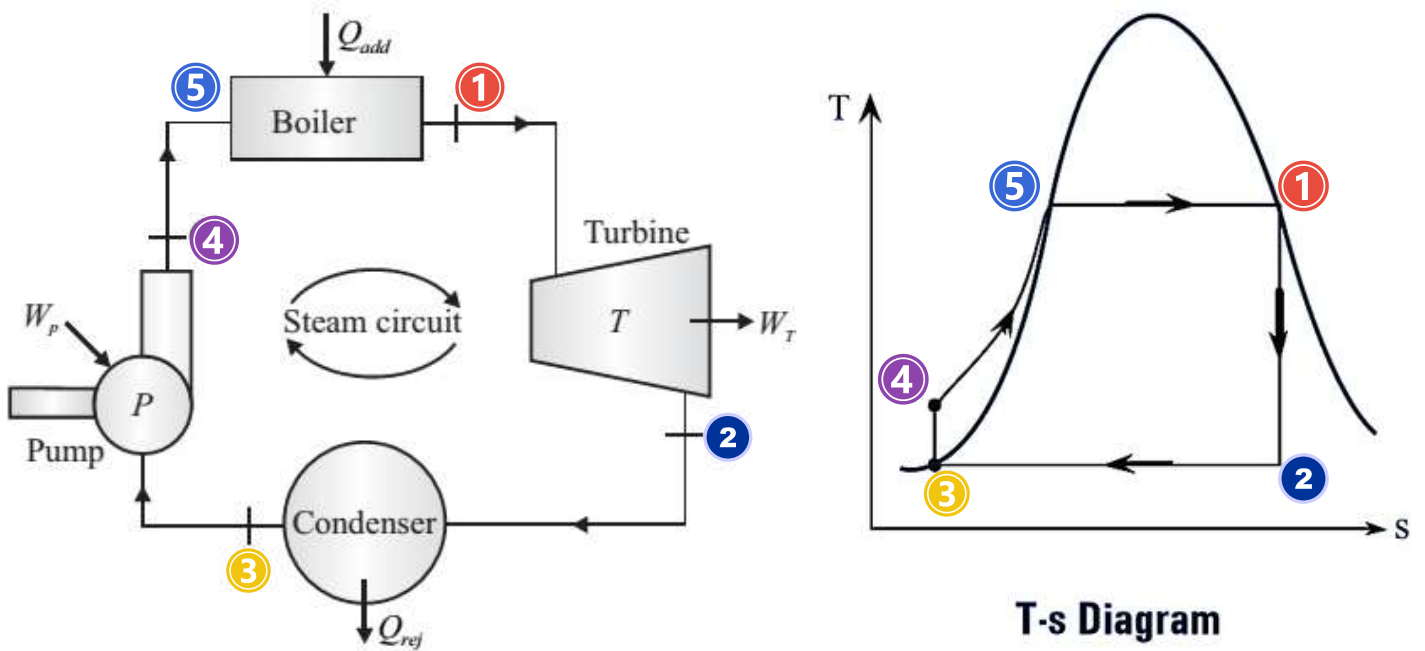


Figure 7 : Rankine Cycle Diagram

<p>BOILER</p> <p>④ → ⑤ → ①</p>	<p>Constant pressure heat addition in a boiler</p> $Q_{451} = h_1 - h_4 \quad (13)$
<p>TURBINE</p> <p>① → ②</p>	<p>Isentropic expansion taking place in the turbine or engine</p> $W_{12} = (h_1 - h_2) \quad (14)$
<p>CONDENSER</p> <p>② → ③</p>	<p>Constant pressure heat rejection in the condenser</p> <p>Heat rejected in condenser = $h_2 - h_3$ (15)</p>
<p>PUMP</p> <p>③ → ④</p>	<p>Isentropic compression of water in the feed pump</p> <p>Work input to pump = $(h_4 - h_3)$ (16)</p>



THERMAL EFFICIENCY OF RANKINE CYCLE



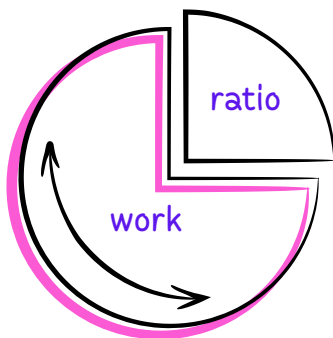
$$\eta_R = \frac{\text{Net Work Output}}{\text{Heat supplied in the boiler}}$$

$$\eta_R = \frac{(W_T - W_P)}{Q_B}$$

$$\eta_R = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)} \quad (17)$$

THE WORK RATIO FOR RANKINE CYCLE

The work ratio is defined by :



$$\text{Work ratio} = \frac{\text{net work}}{\text{gross work}}$$

$$\text{Work Ratio } (W_r) = \frac{(W_T - W_P)}{W_T}$$

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

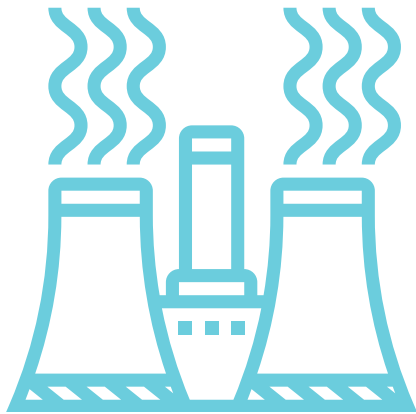
$$W_r = \frac{(h_1 - h_2) - v_f(P_4 - P_3)}{(h_1 - h_4)}$$



When the feed pump term is included, it is necessary to evaluate the quantity, W_{34} . From equation (16)

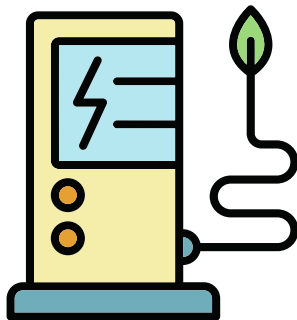
$$\text{Pump work} = -W_{34} = v_f(p_4 - p_3) \quad (18)$$

SPECIFIC STEAM CONSUMPTION



Specific Steam Consumption or Steam Rate (SSC) is the mass flow rate of steam required to produce 1 kW net work output.

$W \times (\text{specific steam consumption, s.s.c.}) = 1 \times 3600 \text{ kJ/h}$
(where W is in kJ/kg),



$$\text{s. s. c} = \frac{3600}{(W_T - W_P)} \text{ kg/kwh}$$

$$\text{s. s. c} = \frac{3600}{(h_1 - h_2) - (h_4 - h_3)} \text{ kg/kwh}$$

Example

A steam power plant operates between a boiler pressure of 40 bar and a condenser pressure of 0.035 bar. Calculate for these limits the cycle efficiency, the work ratio, and the specific steam consumption for a Rankine cycle with dry saturated steam at entry to the turbine.

Solutions :

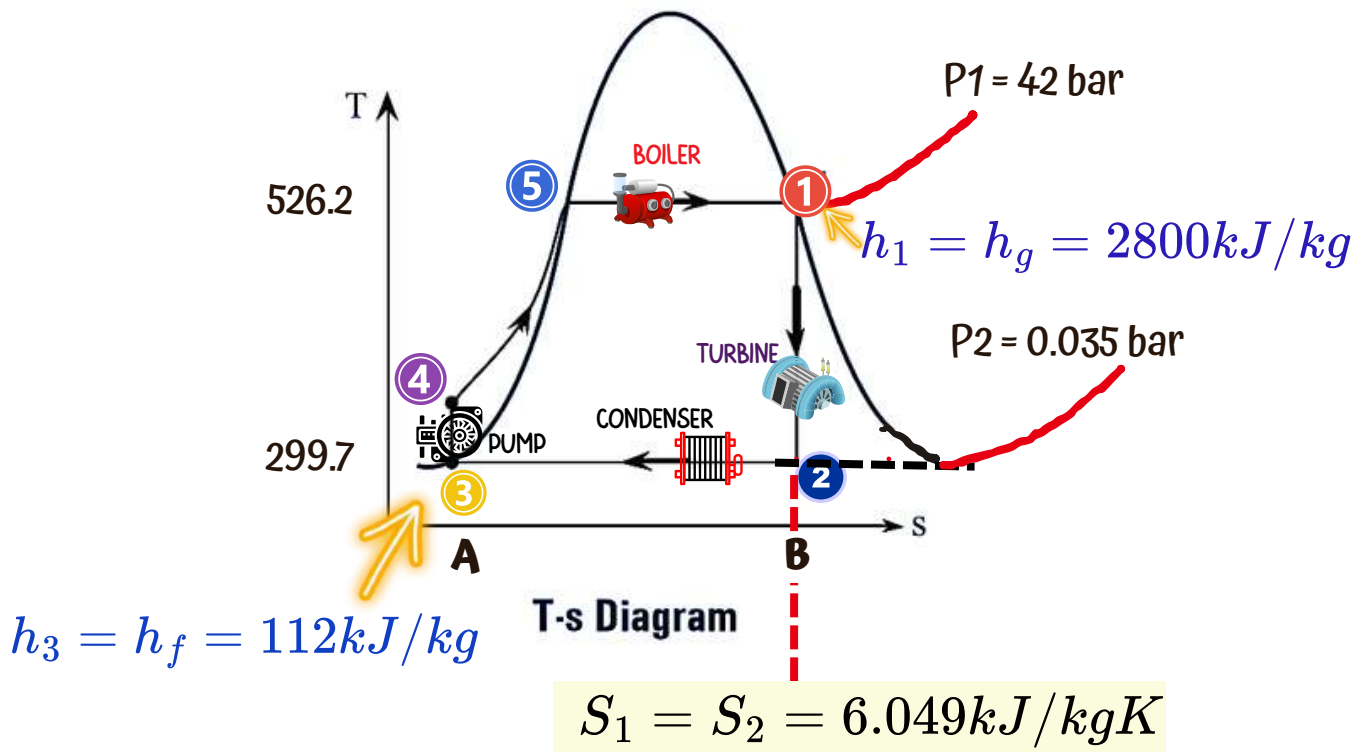


Figure 8 : T-s Diagram (Rankine Cycle)

How to find the Cycle Efficiency

1 Find h_2
 To find the gross work of the expansion process it is necessary to calculate h_2 , using the fact that $s_1 = s_2$. From the steam tables,


At $P_2 = 0.035 \text{ bar}$

Find dryness fraction, x

$$s_1 = s_2 = 6.049 \text{ kJ/kg K}$$

$$s_2 = 6.049 = s_{f2} + x_2 s_{fg2} = 0.391 + x_2 8.13$$

$$x_2 = \frac{6.049 - 0.391}{8.13} = 0.696 \quad \checkmark$$



Find h_2

$$\begin{aligned}h_2 &= h_{f2} + x_2 h_{fg2} \\ &= 112 + 0.696 \times 2438 \\ &= \mathbf{1808 \text{ kJ/kg}} \quad \checkmark\end{aligned}$$

2 Value of Work in Turbine (W_{12}) & Pump Work (W_{34})



Find Work in Turbine

$$\begin{aligned}W_{12} &= (h_1 - h_2) \\ &= (2800 - 1808) \\ &= \mathbf{992 \text{ kJ/kg}} \quad \checkmark\end{aligned}$$



Find Pump Work

$$\begin{aligned}\text{Pump work} &= -W_{34} = v_f (p_4 - p_3) \\ &= 0.001 \times (42 - 0.035) \times 10^2 \\ &= \mathbf{4.2 \text{ kJ/kg}} \quad \checkmark\end{aligned}$$

3

Find Thermal efficiency of Rankine cycle



Thermal Efficiency

$$\eta_R = \frac{(W_T - W_P)}{Q_B}$$

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

$$= \frac{(961.7) - (4.0)}{(2801 - 130) - (4.0)}$$

$$= 0.359 \text{ or } 35.9 \% \quad \checkmark$$

4

Find The Work Ratio



The Work Ratio

$$\text{Work ratio} = \frac{\text{net work}}{\text{gross work}}$$

$$= \frac{961.7 - 4.0}{961.7}$$

$$= 0.996 \quad \checkmark$$

S

Find The Specific Steam Consumption (S.S.C)



The Specific Steam Consumption (S.S.C)

$$\text{s.s.c.} = \frac{3600}{(h_1 - h_2) - (h_4 - h_3)}$$

$$= \frac{3600}{(961.7) - (4.0)}$$

$$= \mathbf{3.76 \text{ kg/kW h}}$$
 

EXERCISE

Final Examination Question

SET 1

- (a) List **FOUR (4)** characteristic of reversed heat engine.
- (b) A Carnot heat engine operates with an efficiency of 44% and rejects heat to the atmosphere at the temperatures of 38 oC. Relate the information given for solution of hot reservoir temperature value in oC unit.
- (c) A steam power plant operates between a boiler pressure of 50 bar and and a condenser pressure of 0.75 bar. If steam enters the turbine with dry saturated condition, calculate for a Rankine cycle :
- (i) Feed pump work
 - (ii) Rankine efficiency
 - (iii) Specific steam consumption

Answer

(b) $T_h = 282.35\text{oC}$;

(c) (i) Feed pump work = 4.295 kJ/kg ; (ii) Rankine efficiency = 28% ; (iii) S.S.C = 5.343 kg/kWhr

SET 2

- (a) Describe **TWO (2)** characteristics for heat engine and **TWO (2)** characteristics for reverse heat engine.
- (b) Heat is transferred to a heat engine from a furnace at a rate of 70000 kW. If the rate of waste heat rejection to a nearby river is 35 MW, express the value of nett work done and the efficiency for this heat engine.
- (c) A Rankine steam power plant operates between a boiler pressure of 4400 kPa and condenser pressure of 0.03 bar. Of steam entry to the turbine with dry saturated, calculate :
- (i) Turbine work
 - (ii) Feed pump work
 - (iii) Rankine cycle efficiency

Answer

(b) Nett Work Done , $W = 35 \text{ MW}$; Thermal Efficiency = 50%

(c) (i) Turbine work = 1010.64kJ/kg ; (ii) Feed Pump work = 4.397 kJ/kg ; (iii) Rankine efficiency = 37.37%

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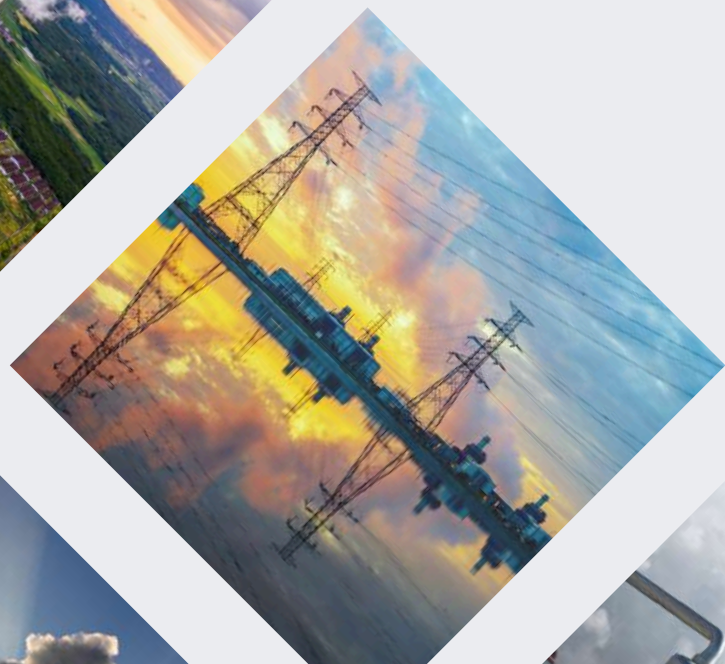
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