

Mechanical Engineering

Power Plant Engineering

Comprehensive Theory

with Solved Examples and Practice Questions



MADE EASY
Publications



MADE EASY Publications

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016

E-mail: infomep@madeeasy.in

Contact: 011-45124660, 8860378007

Visit us at: www.madeeasypublications.org

Power Plant Engineering

© Copyright by MADE EASY Publications.

All rights are reserved. No part of this publication may be reproduced, stored in or introduced into a retrieval system, or transmitted in any form or by any means (electronic, mechanical, photo-copying, recording or otherwise), without the prior written permission of the above mentioned publisher of this book.

First Edition: 2015

Second Edition: 2016

Third Edition: 2017

Fourth Edition: 2018

Fifth Edition: 2019

Sixth Edition: 2020

Contents

Power Plant Engineering

Chapter 1

Steam Power Plant..... 1

1.1	Introduction	1
1.2	Boiler	1
1.3	Classification of Boilers.....	2
1.4	Fire Tube Boiler	3
1.5	Water Tube Boiler.....	3
1.6	Steam Drum.....	4
1.7	Economisers	8
1.8	Superheaters	9
1.9	Reheater.....	10
1.10	Electro-Static Precipitator (ESP).....	10
1.11	Ash Handling System	11
1.12	Feedwater Treatment	11
1.13	High Pressure Boiler.....	12
1.14	Super Critical Boiler (once through or monotube boiler)	14
1.15	Boiler Mountings	15
1.16	Boiler Accessories	15
1.17	Comparison between “Fire Tube and Water Tube Boilers”	17
1.18	Fluidized Bed Boiler	17
1.19	Steam Generator Control.....	20
	<i>Objective Brain Teasers</i>	23
	<i>Student's Assignments</i>	25

Chapter 2

Fuels and Combustion.....26

2.1	Introduction	26
2.2	Coal	26
2.3	Coal Analysis.....	27
2.4	Coal Properties	28
2.5	Actual Air-Fuel Ratio.....	29

2.6	Cooling Limit of Exhaust Gas.....	30
2.7	Control of Excess Air	31
2.8	Draught (or Draft) System	32
2.9	Fans	35
	<i>Objective Brain Teasers</i>	36
	<i>Student's Assignments</i>	38

Chapter 3

Analysis of Steam Cycles39

3.1	Introduction.....	39
3.2	Carnot Cycle.....	39
3.3	Rankine Cycle	41
3.4	Deviation of Actual Cycle from Theoretical Rankine Cycle	44
3.5	Improvement in Rankine Cycle.....	44
3.6	Super Critical Pressure Cycle.....	52
3.7	Various Efficiencies of Steam Power Plants	52
	<i>Objective Brain Teasers</i>	58
	<i>Student's Assignments</i>	59

Chapter 4

Cogeneration and Combined Cycle.....60

4.1	Introduction	60
4.2	Back Pressure Turbine.....	60
4.3	Pass-out Turbine.....	62
4.4	Combined Cycle Power Generation	62
4.5	Characteristics of Ideal Working Fluid for Vapour Power Cycle.....	63
4.6	Binary Vapour Cycles	63
4.7	Combined Cycle Plants	64
	<i>Objective Brain Teasers</i>	70
	<i>Student's Assignments</i>	70

Chapter 5

Steam Turbines71

5.1	Introduction.....	71
5.2	Classification of Steam turbine	71
5.3	Simple Impulse Turbines.....	72
5.4	Compounding of Steam Turbines.....	72
5.5	Impulse Reaction Turbine	75
5.6	Comparison of Impulse and Reaction Turbine.....	75
5.7	Impulse Turbine Analysis	76
5.8	Reaction Turbine Analysis.....	88
5.9	Parsons Turbine (50% reaction turbine)	90
5.10	Enthalpy Drop in Various Stages	99
5.11	Losses in Steam Turbines	102
	<i>Objective Brain Teasers</i>	107
	<i>Student's Assignments</i>	110

Chapter 6

Gas Turbine111

6.1	Introduction	111
6.2	Open Cycle Arrangements.....	111
6.3	Closed Cycle Arrangement	112
6.4	Requirements of the Working Medium.....	114
6.5	Advantages of Gas Turbines Over Reciprocating Engines.....	114
6.6	Ideal Open Gas Turbine Cycle.....	114
6.7	Actual Cycle Analysis.....	117
6.8	Optimum Pressure Ratio.....	121
6.9	Cycle with Regeneration or Heat Exchange Cycle	122
6.10	Cycle with Reheating	124
6.11	Cycle with Reheating and Regeneration	125
6.12	Cycle with Intercooling	127
6.13	Cycle with Intercooling and Regeneration	128

6.14	Cycle with Intercooling and Reheating.....	129
6.15	Cycle with Intercooling, Reheating and Regeneration	130
6.16	Comparison of Various Cycles.....	140
6.17	Performance Curves.....	141
6.18	Polytropic Efficiency (η_p).....	143
	<i>Objective Brain Teasers</i>	152
	<i>Student's Assignments</i>	155

Chapter 7

Reciprocating Air Compressors157

7.1	Introduction.....	157
7.2	Work Input for Compression Process.....	158
7.3	Equation of Work (with Clearance Volume).....	160
7.4	Volumetric Efficiency (hvol)	161
7.5	Multistage Compression	163
7.6	Effect of Clearance Volume	168
7.7	Actual P-V Diagram for Single-Stage Compressor.....	174
	<i>Objective Brain Teasers</i>	177
	<i>Student's Assignments</i>	179

Chapter 8

Rotary Compressor180

8.1	Introduction.....	180
8.2	Centrifugal Compressor	180
8.3	Axial Flow Compressors	192
8.4	Comparison between the Centrifugal and Axial Flow Compressor.....	198
8.5	Root Blower.....	206
8.6	Vane Type Blower.....	207
	<i>Objective Brain Teasers</i>	212
	<i>Student's Assignments</i>	215

Chapter 9

Compressible Fluid Flow & Nozzle217

9.1	Introduction.....	217
9.2	Static Properties	217
9.3	Stagnation Properties	217
9.4	Velocity of Sound (Sonic Velocity)	219
9.5	One Dimensional Steady Isentropic Flow (Effect of Area Variation)	221
9.6	Nozzles.....	223
9.7	Flow Through Nozzles.....	224
9.8	Super Saturated Flow	228
9.9	Types of Nozzle.....	229
9.10	Fanno and Rayleigh Lines.....	232
	<i>Objective Brain Teasers</i>	243
	<i>Student's Assignments</i>	246

Chapter 10

Nuclear Power Plants247

10.1	Introduction.....	247
10.2	Isotopes	248
10.3	Nuclear Stability and Binding Energy.....	248
10.4	Radioactive Decay and Half Life	249
10.5	Nuclear Reactor & Essential Components.....	251
10.6	Selection of Fuel and Moderator.....	252
10.7	Types of Reactors	253
10.8	Pressurised Water Reactor (PWR)	253
10.9	Boiling Water Reactor (BWR).....	255
10.10	CANDU Reactor	257
10.11	Gas Cooled Reactor.....	258
10.12	Breeder Reactors.....	258

10.13	Liquid Metal Fast Breeder Reactor (LMFBR)	259
10.14	Advantages and Disadvantages of Nuclear Power Plant.....	262
10.15	Nuclear Waste Disposal	263
10.16	Nuclear Power Programme of India	263
10.17	Location of Nuclear Power Plant	264
	<i>Objective Brain Teasers</i>	265
	<i>Student's Assignments</i>	268

Chapter 11

Jet Engines269

11.1	Introduction.....	269
11.2	Atmospheric Jet Engine or Air Breathing Engines	269
11.3	Rocket Engine or Non Air Breathing Engines ..	269
11.4	Reciprocating or Propeller Engines.....	269
11.5	Gas Turbine Engines	270
11.6	Ramjet Engines.....	270
11.7	Pulse Jet Engine.....	272
11.8	Turboprop Engine	274
11.9	Turbojet Engine	275
11.10	Parameters Affecting Performance	289
11.11	Advantages of Jet Propulsion over Other System.....	290
11.12	Comparison of Relative Performances of Various Propulsion Power	291
11.13	Rocket Engine	291
11.14	Solid Propellant Rockets.....	294
11.15	Liquid Propellant Rockets	295
	<i>Objective Brain Teasers</i>	296
	<i>Student's Assignments</i>	299

Chapter 12

Steam Condensers, Cooling Tower & Air Ejector.....300

Steam Condenser

12.1	Introduction.....	300
12.2	Vacuum.....	300
12.3	Organs of a Steam condensing Plant	301
12.4	Classification of Condensers.....	301
12.5	Jet Condensers	301

Ejector Condenser

12.6	Surface Condensers	303
12.7	Reasons for Inefficiency in Surface Condensers	306
12.8	Comparison Between Jet and Surface Condensers	306
12.9	Selection of Condenser	307
12.10	Sources of Air in Condensers	307

12.11	Effects of Air Leakage in Condenser	307
12.12	Method for Obtaining Maximum Vacuum in Condensers	308
12.13	Vacuum Measurement.....	308
12.14	Vacuum Efficiency	309
12.15	Condenser Efficiency.....	309
12.16	Determination of Mass of Cooling Water.....	309
12.17	Heat Transmission through Walls of Tubes of a Surface condenser.....	310
12.18	Methods of Cleaning Condenser Tubes.....	311
12.19	Cooling Tower	312
12.20	Dry Cooling Towers	315
12.21	Maintenance of Cooling Towers	316

Air Ejector

12.22	Air Ejector Working	319
12.23	Air Ejector Theory	319
12.24	Application of Air Ejectors	319



Analysis of Steam Cycles

3.1 Introduction

Steam power plants work on the basis of some thermodynamic cycle, such as Carnot cycle and Rankine cycle. Carnot cycle is an ideal and most efficient cycle but is not practically feasible. Coal based power stations are using Rankine cycle.

A steam power plant continuously converts the chemical energy of the fossile fuels or fissile fuels into mechanical energy and ultimately into electrical energy. The working substance is water which is some times in the liquid phase and sometimes in the vapour phase.

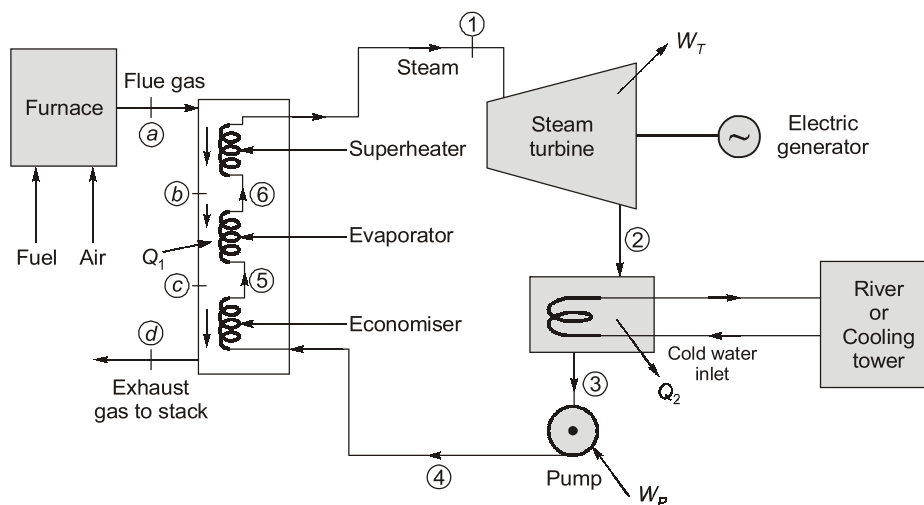


Fig. 3.1

3.2 Carnot Cycle

This cycle was proposed by Sadi Carnot. Under Carnot cycle the working substance receives heat at temperature and rejects at another temperature. The cycle consists of **two isothermal** processes and **two reversible adiabatic** processes, as shown in fig 3.2.

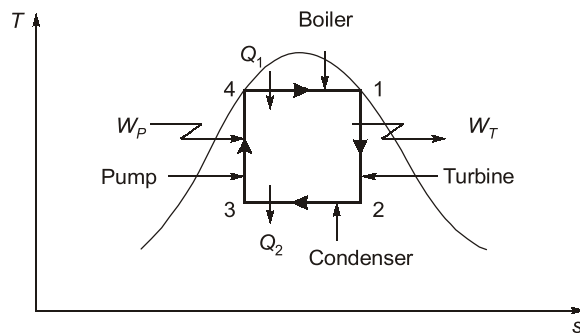


Fig. 3.2

Process 1–2: Isentropic (reversible adiabatic) expansion.

Process 2–3: Reversible isothermal heat rejection

Process 3–4: Isentropic (reversible adiabatic) compression

Process 4–1: Reversible isothermal heat addition

All the above processes of Carnot cycle are reversible hence the entire cycle is also reversible. The same can also be represented by a heat engine which operates between two thermal reservoirs maintained at temperature T_1 and T_2 and produces the work W .

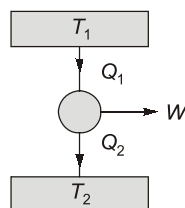


Fig. 3.3

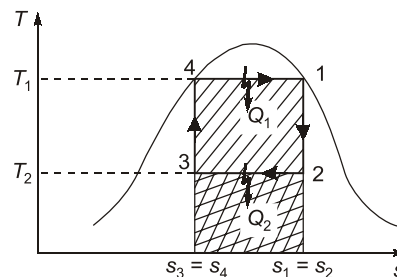


Fig. 3.4

The single line hatched area enclosed by points 1, 2, 3, 4 represents the net heat ($Q_1 - Q_2$) or net work ($W_T - W_P$) interaction, and the double line or crossed hatched area represents heat rejection, (Q_2).

For a substance undergoing a cyclic change, cyclic integral of work is equal to the cyclic integral of heat. Thus,

$W_T - W_P = Q_1 - Q_2$, and efficiency (η) can be represented by

$$\eta = \frac{\text{Net work}}{\text{Heat supplied}} = \frac{W_T - W_P}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2(s_2 - s_3)}{T_1(s_1 - s_4)} = 1 - \frac{T_2}{T_1}$$

Since the area under a process on T - s diagram represents the heat interaction.

3.2.1 Limitations of Carnot Cycle

1. **Termination of condensation process** is not practically feasible at point 3 from where compression leads to point 4 on saturation line, *i.e.*, water in saturated condition and needs only latent heat for conversion into vapour.
2. During compression of the **mixture of steam and water** in the pump from point 3 to point 4, steam is getting condensed and vanishes at the end of compression. When steam gets converted into water, a large difference in specific volume causes cavitation over the impellers. The cavitation damage the impeller due to which impeller requires frequent replacement.

- Any pump cannot suck the mixture of water and its vapour at state point 3 and deliver saturated liquid at state point 4, which is the need of Carnot cycle.
- If exhaust steam from turbine is completely cooled in condenser, then transfer of heat at constant temperature (6'–4) and infinite pressure gradient is not possible. **Addition of heat at constant temperature is possible only within the dome.** Outside the dome, i.e., either in sub-cooled region or superheat region this is not possible.

3.3 Rankine Cycle

Limitation of Carnot cycle can be overcome by complete condensation of vapour up to point 3' (shown as in figure 3.5) as a large amount of cooling water is supplied in the condenser. The water thus formed is pumped to point 4' and sent to the boiler for **addition of sensible and latent heat** to get it converted into steam. The area under 3'–4'–4 is sensible heat addition and area under 4–1 is latent heat addition. The cycle thus formed by the process 1–2–3'–4'–4–1 becomes Rankine cycle, which is being used in thermal power plants with modifications to induce superheaters, regenerator and reheater.

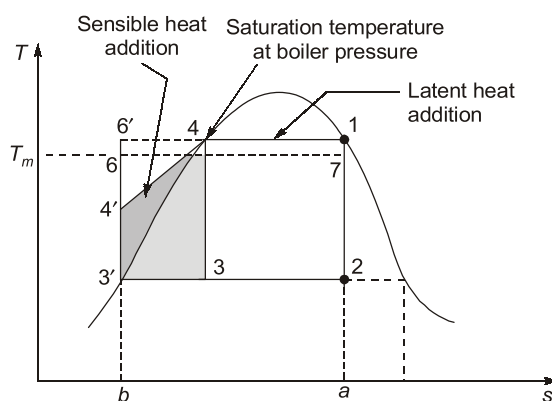


Fig. 3.5

This cycle contains four processes:

- ❖ **Boiler:** Reversible constant pressure heating process of water
- ❖ **Turbine:** Reversible adiabatic expansion of steam.
- ❖ **Condenser:** Reversible constant pressure heat rejection
- ❖ **Pump:** Reversible adiabatic compression.

When all these four processes are ideal the cycle is an ideal cycle, called a **Rankine cycle**.

3.3.1 Calculation of Mean Temperature (T_m)

In the Rankine cycle, heat is added reversibly at a constant pressure but at infinite temperatures. If T_m is the mean temperature of heat addition, then

$$\text{Heat added: } q_1 = h_1 - h'_4 = T_m (s_2 - s'_3)$$

$$\text{or } T_m = \frac{h_1 - h'_4}{s_2 - s'_3}$$

3.3.2 Comparison of Carnot and Rankine Cycles

$$\text{Efficiency of Carnot cycle, } \eta_C = 1 - \frac{T_2}{T_1}$$

For comparison, let us assume that the entire heat addition in Rankine cycle also takes place at some imaginary temperature T_m , i.e., area $b-4'-4-1-a-b$ = area $b-6-7-a-b$. Thus, the equivalent cycle with heat addition at constant temperature becomes 7–2–3'–6–7, with heat addition at T_m and heat rejection at T_2 . The efficiency of this equivalent cycle becomes:

$$\eta_R = 1 - \frac{T_2}{T_m}, \quad \text{where } T_m < T_1$$

Since T_m is lower than T_1 in Rankine cycle, the efficiency of Rankine is lower than the efficiency of Carnot cycle $\eta_R < \eta_C$.

NOTE

Lower is the condenser pressure, the higher will be the efficiency of the Rankine cycle. Since it is fixed so $\eta_{\text{Rankine}} = f(T_m)$ only.

The higher the mean temperature of heat addition, the higher will be the cycle efficiency.

3.3.3 Analysis of Rankine Cycle

For 1 kg of fluid, the steady flow energy equation to each processes:

For boiler, $q_1 = h_1 - h_4$

For turbine, $w_T = h_1 - h_2$

For condenser, $q_2 = h_2 - h_3$

For pump, $w_P = h_4 - h_3$

Efficiency of Rankine cycle,

$$\eta = \frac{w_{\text{net}}}{q_1} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

The pump work is small compared to the turbine work and is often neglected.

Isentropic Cycle

$$\text{Work ratio} = \frac{\text{Net work}}{\text{Turbine work}} = \frac{w_{\text{net}}}{w_T}$$



Critical temperature and pressure of water are 374°C and 221.2 bar. At all temperature above the critical, it is impossible to liquefy water vapour by using pressure, no matter how great the pressure is employed.

Steam Rate

The capacity of a steam plant is often expressed in terms of steam rate or specific steam consumption. It is defined as the rate of steam flow (kg/s) required to produce unit shaft output (1 kW).

$$\text{Steam rate} = \frac{1}{w_{\text{net}}} \text{ kg/kWs} = \frac{3600}{w_{\text{net}}} \text{ kg/kWh}$$

Heat Rate

The cycle efficiency is sometimes expressed alternatively as heat rate which is the rate of heat input (kJ/s) required to produce unit shaft output (1 kW)

$$\text{Heat rate:} \quad \text{H.R.} = \frac{3600}{\eta_{\text{th}}} = \frac{3600 q_1}{w_{\text{net}}} \text{ kJ/kWh}$$

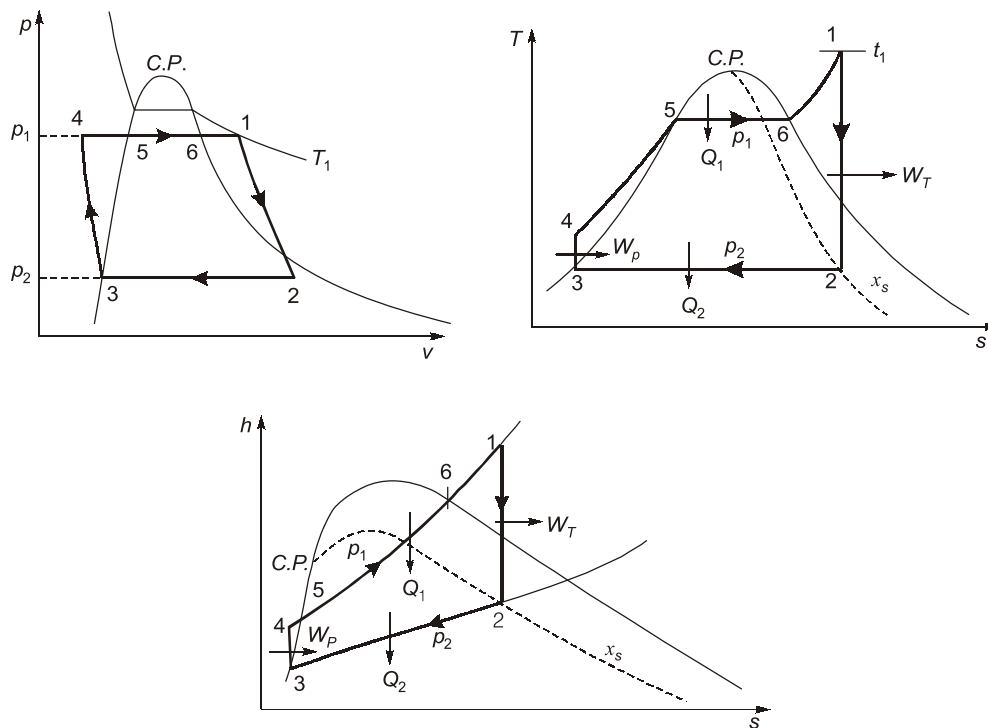


Fig. 3.6

Water is first heated sensibly in the economiser in the liquid phase at a certain pressure till it becomes saturated liquid.

$$q_{Eco} = h_5 - h_4$$

In the evaporator there is phase change or boiling with state changing by-absorbing the latent heat of vapourization at that pressure.

$$q_{Evo} = h_6 - h_5 = h_{fg}$$

The saturated vapour is further heated at constant pressure in the superheater to gaseous phase.

$$q_{SH} = h_1 - h_6$$

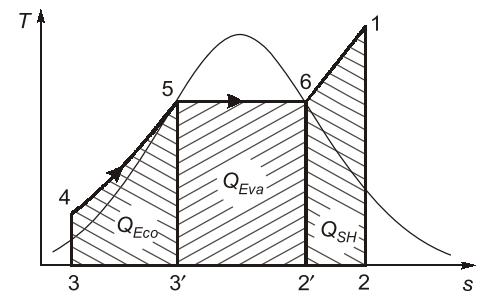


Fig. 3.7

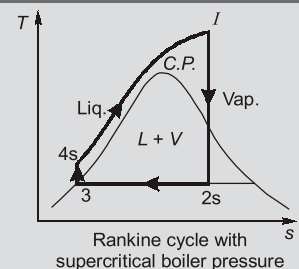
As the pressure increases, the latent heat decreases and so the heat absorbed in the evaporator decreases and the fraction of the total heat absorbed in the superheater increases.

NOTE



For steam generators operating above the critical pressure there is no evaporator or boiling section.

However, there is a transition zone where all the liquid on being heated suddenly flashes into vapour.



leaving the condenser is subcooled by 6.3°C . The boiler is sized for a mass flow rate of 20 kg/s . Determine the rate at which heat is added in the boiler, the power required to operate the pumps, the net power produced by the cycle and the thermal efficiency.

[Ans. 59,660 kW, 122 kW, 18,050 kW, 30.3%]

- Q.3** The closed feedwater heater of a regenerative Rankine cycle is to heat 7000 kPa feedwater from 260°C to a saturated liquid. The turbine supplies bleed steam at 6000 kPa and 325°C to this unit. This steam is condensed to a saturated liquid before entering the pump. Calculate the amount of bleed steam required to heat 1 kg of feedwater in this unit.

[Ans. 0.0779 kg/s]

- Q.4** A steam power plant operates on an ideal regenerative Rankine cycle with two open feedwater heaters. Steam enters the turbine at 10 MPa and 600°C and exhausts to the condenser at 5 kPa . Steam is extracted from the turbine at 0.6 and 0.2 MPa . Water leaves both feedwater heaters as a saturated liquid. The mass flow rate of steam through the boiler is 22 kg/s . Show the cycle on a T - s diagram, and determine

- (a) the net power output of the power plant and
- (b) the thermal efficiency of the cycle

[Ans. (a) 30.5 MW , (b) 47.1%]

Note: Use steam table if required.

■■■■