WORKED EXAMPLES IN

ENGINEERING THERMODYNAMICS

Second (revised) Edition

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Worked Examples in Engineering Thermodynamics

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PREFACE TO THE SECOND EDITION

The field covered by this book is that of an undergraduate applied thermodynamics course such as the University of London B.Sc. (Engineering) Degree Parts 1, 2 and 3; the Associate Membership examinations of the Professional Institutions; Diploma in Technology (Engineering); College Diplomas and the Higher National Diploma and Certificate examinations.

The book has been compiled as the result of the extensive use made by students of a collection of worked examination questions, particularly during the final revision period.

The solutions are intended to be those which an examiner might reasonably expect in the time allowed for the questions. For this reason undue explanation of the methods used is not given. The authors hope that this will also help students to think for themselves.

The questions have been grouped at the beginning of each chapter because it is felt that model solutions are only of value after the student has obtained his own solution. A question immediately followed by its solution cannot be studied separately even with the best intentions. It is realised that this arrangement will cause some back reference but this should not prove unduly inconvenient.

Examination questions do not always fall conveniently into even twenty divisions and it has therefore been difficult in some cases to decide on appropriate chapter headings. It is felt that the provision of a detailed subject index should readily overcome this.

Theory other than that specifically demanded by the question is not given and any student not attending lectures should use this book in conjunction with a standard "Thermodynamics" textbook. A few special references will be found in the solutions.

This edition has given the opportunity to approach the subject from the modern viewpoint with the result that some problems have been replaced or rearranged and new ones added. The symbols agree with BS 1991—Part 5; notable exceptions being the special symbols for chapters 5 and 6, the use of °F for both temperature point and difference and the use of V for both volume and specific volume in order to avoid confusion with velocity. Abridged Callendar Steam Tables 4th edition and Total Heat-Entropy Chart for Steam 1939, both in Fahrenheit Units and published by Edward Arnold & Co., have been used throughout.

Calculations have been made with the slide rule except where otherwise indicated and every effort has been made to avoid errors. It cannot be hoped however that all mistakes have been discovered and the authors will appreciate comments from readers.

The authors acknowledge with thanks permission to reprint questions from the examination papers of the following bodies: The Senate of the University of London; the Councils of the Institutions of Civil and Mechanical Engineers; the Union of Educational Institutions; the Union of Lancashire and Cheshire Institutes; and the East Midlands Educational Union, and from the Principal and Governors of Brighton College of Technolgoy.

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CONTENTS

		Page
	Preface	v
	Symbols and Constants	ix
	Abbreviations for Examining Bodies	xi
1.	Steam	13
2.	The Reciprocating Steam Engine	40
3.	The Rankine Cycle and its Modifications	60
4.	Steam Nozzles	81
5.	Impulse Steam Turbine Blade Calculations	109
6.	Reaction Steam Turbine Blade Calculations	129
7.	Feed Heating and Reheating in Turbine Circuits	143
8.	Turbine Plant and Performance	164
9.	Steam Boilers	192
10.	Condensers	213
11.	Partial Pressures	225
12.	Properties of Gases	253
13.	Ideal Internal Combustion Engine Cycles	283
14.	Performance of Internal Combustion Engines	307
15.	Fuels and Combustion with Reference to Internal Combustion Engines	344
16.	Reciprocating Air Compressors	374
17.	Rotary and Turbo-Compressors	405
18.	Gas Turbines	424
19.	Heat Transfer	457
20.	Refrigeration	484
	Appendix: Additional Examples	525
	Answers	543
	Index	545

SYMBOLS

A	area
$°C$	degree Celsius (point and difference)
c	specific heat (specific heat capacity)
d	diameter
D	diameter
E	energy (all forms)
$°F$	degree Fahrenheit (point and difference)
G	Gibbs function
g	Gibbs function specific
g	acceleration due to gravity
g_c	dimensional constant (e.g. 32·2 lb ft/lbf s^2
H	enthalpy
h	enthalpy specific
h	coefficient of heat transfer; blade height
J	Joule's mechanical equivalent of heat
k	thermal conductivity
$°K$	degree Kelvin (point and difference)
L	stroke length
l	length
M	molecular "weight"
m	mass; mass flow rate
N	frequency of rotation
n	polytropic index
n	number of moles; number of working cycles
P	total pressure
p	pressure (static); mean effective pressure
Q	quantity of heat
R	gas constant, particular; radius
R_0	gas constant, molar (universal)
$°R$	degree Rankine (point and difference)
r	ratio, compression or expansion; radius

S	entropy
s	entropy specific
T	absolute temperature; total temperature
t	temperature (static); time
U	internal energy
u	internal energy specific
U	overall coefficient of heat transfer; velocity (turbine problems)
u	speed of rotor blades
V	volume
v	velocity
W	work
x	dryness fraction; path length
α	angle
β	angle
γ	angle; ratio of specific heats
δ	angle
Δ	finite increment
η	efficiency
θ	temperature (chapter 19)

SUBSCRIPTS

f	saturated liquid
g	dry saturated vapour
fg	evaporation
p	constant pressure
v	constant volume
s	constant entropy

Other subscripts are used in local contexts.

Some additional symbols are given for Chapters V and VI.

The following values are used throughout:

$T°\,R = t°\,F + 460.$

s.t.p. = 14·7 lbf/in^2; 32° F.

1 mole occupies 359 ft^3, at s.t.p.

1 inch mercury = 0·49 lbf/in^2.

(For air $\gamma = 1{\cdot}4$ $R = 53{\cdot}3$ ft-lbf/lb° R unless otherwise given.)

Abbreviations for Examining Bodies

U.Lond.	University of London.
U.L.C.I.	Union of Lancashire and Cheshire Institutes.
U.E.I.	Union of Educational Institutions.
E.M.E.U.	East Midland Educational Union.
I.C.E.	Institution of Civil Engineers.
I.Mech.E.	Institution of Mechanical Engineers.
H.N.D.	Higher National Diploma—Brighton Technical College.
H.N.C.	Higher National Certificate—Brighton Technical College.
B.C.T.	Brighton College of Technology.

1

STEAM

1. What is the essential difference between the Enthalpy and the Internal Energy of steam?

Dry saturated steam at 50 lbf/in^2 is expanded according to the law $pV^{1\cdot1}$ = constant to 20 lbf/in^2.

Find (a) the final dryness of the steam;

(b) the internal energy per pound at the lower pressure.

(U. Lond.)

2. Dry steam at 250 lbf/in^2 is throttled down to 200 lbf/in^2 and then expanded adiabatically to 4 lbf/in^2. Using steam tables (but not a mollier chart) find (a) the temperature of the low pressure steam, (b) the gain of entropy during throttling, (c) the dryness of the steam at the end of expansion, (d) the work done per pound of steam during expansion. (U.E.I.)

3. Two rigid vessels of equal volume are interconnected via a valve. Initially the valve is closed and one vessel contains 0·3 lb of dry-saturated steam at a pressure of 80 lbf/in^2 whilst the other vessel is completely evacuated. After the valve is opened and equilibrium of pressure and temperature has been reached, the pressure is observed to be 60 lbf/in^2. Find the magnitude and sign of the heat transfer to the steam. (U. Lond.)

4. One pound of dry saturated steam at 150 lbf/in^2 is contained in a cylinder. If it expands adiabatically behind a piston to 15 lbf/in^2 find the work done per pound during expansion. If an engine is supplied with steam at 150 lbf/in^2 dry and saturated and the steam expands adiabatically to 15 lbf/in^2, what is the work done per pound of steam.

(U.E.I.)

5. A cylinder contains 0·5 lb of dry saturated steam at a temperature of 281° F. The temperature is reduced to 180° F, the volume being kept constant. Find the amount of heat lost by the steam in the cooling process.

If, however, the steam had been allowed to do work by expanding adiabatically against a piston until the temperature had fallen to 180° F, what would then have been the state of the steam at the end of expansion? (U. Lond.)

6. A pressure vessel has a capacity of 24 cubic feet. Initially it contains steam at 50 lbf/in^2 and 0·9 dry. A valve is then opened connecting the vessel to a main which supplies steam at a steady pressure of 200 lbf/in^2 and 0·93 dry. The valve remains open until the pressure in the vessel has risen to 150 lbf/in^2. Ignoring steam velocity in the main and heat loss from the vessel, calculate the mass of steam supplied to the vessel and the final condition of the steam in the vessel. (U. Lond.)

7. A rigid vessel is initially divided into two parts A and B by a thin partition. Part A contains 1 lb of steam at 50 lbf/in^2, dry and saturated, and part B 2 lb of steam at 100 lbf/in^2 with a dryness fraction of 0·8.

The partition is removed and the pressure in the vessel after some time is found to be 70 lbf/in^2.

Find (a) the volume of the vessel, and the state of the steam at 70 lbf/in^2, (b) the amount of heat transfer from the steam to the vessel and the surroundings. (U. Lond.)

8. The steam in the cylinder of an engine expands according to a law $pV^{1 \cdot 1}$ = constant. The initial and final steam pressures are respectively 60 and 20 lbf/in^2, while the initial steam dryness fraction is 0·95.

Determine, per pound of steam:

(a) the final volume;

(b) the work done;

(c) the heat interchange between the steam and the cylinder walls, stating whether this is a reception or a rejection by the steam. (U. Lond.)

9. Distinguish between enthalpy and internal energy of steam. Prove that enthalpies before and after a throttle are equal. Steam at 100 lbf/in^2, 0·94 dry is throttled to 20 lbf/in^2 and passed slowly at this pressure through a casing in which a turbine disc is rotated by external power. Neglecting friction, find the dryness of the steam leaving the casing, if the flow is 1·04 lb/s and the horse-power absorbed by friction of the disc is 7·2. (U. Lond.)

10. At a point just after cut-off in a steam engine cylinder the steam pressure was 150 lbf/in^2 and the dryness 0·85. After expansion, at a point just before release, the pressure was 60 lbf/in^2 and the dryness 0·80. Assuming that expansion obeys a law pV^n = a constant, determine the heat exchange per pound between the steam and the cylinder walls, and state whether it is a gain or a loss by the steam. (U. Lond.)

11. Steam at a pressure of 150 lbf/in^2 and 0·95 dry is condensed at this pressure in a coil immersed in water. This water, which is at saturation temperature, is contained in a vessel in which the pressure is maintained at 60 lbf/in². Steam of dryness 0·90 is evaporated from this water and is passed through a throttle valve into a pipe line. The pressure in the pipe is 20 lbf/in².

Assuming complete interchange of heat between the steam in the coil and the water in the vessel, and neglecting loss of heat by radiation, etc., calculate—

(a) the mass of high-pressure steam required per pound of low-pressure steam,
(b) the diameter of pipe required for a flow of 4 lb of low-pressure steam/min if the velocity in the pipe is 60 ft/s. (U. Lond.)

12. Explain how a combined separating and throttling calorimeter may be used to estimate the dryness of steam in a steam main. Make suitable sketches to show the construction and how the sample is taken.

In such an arrangement, the steam main pressure is 120 lbf/in² and the temperature after throttling is 265° F. The pressure in the throttling calorimeter is 3·2 in of mercury, the barometer being 29·50 in. At the separator 0·33 lb of water is trapped and 3·95 lb of steam are passed through the throttling calorimeter.

Determine the dryness of the steam in the steam main, using the steam tables provided to find the enthalpy per pound of the superheated steam. (U. Lond.)

13. An engine is supplied with steam from a boiler through a long pipe-line. The steam leaving the boiler is at 200 lbf/in² and 400° F. Some of the steam at the engine end of the pipe-line is bled off and passed through a throttling calorimeter: the steam temperature entering the calorimeter is 381·8° F, while the pressure and temperature of the steam after passing through the calorimeter are respectively 15 lbf/in² and 240° F.

Determine:

(a) the heat-loss per pound of steam during passage through the pipe,
(b) the steam dryness at the engine,
(c) the change in volume per pound of the steam during passage through the pipe. (U. Lond.)

14. Show that when a system undergoes a fully resisted constant-pressure process the heat transfer between the system and its surroundings is equal to the increase in the enthalpy of the system.

A mixture of 0·1 lb of saturated water and 0·9 lb of saturated steam at a temperature of 460·7° F is contained in a vertical cylinder closed by a frictionless leakproof piston. The mixture supports the piston and the upper surface of the piston is exposed to the atmospheric pressure, 15 lbf/in^2; there is no piston rod. Heat transfer to the mixture causes its temperature to rise slowly to 550·7° F.

Evaluate the heat transfer to the mixture and the work done by the piston.

(U. Lond.)

15. A closed drum contains 300 lb of steam, 0·5 dryness fraction, at 15 lbf/in^2. What mass of dry saturated steam at 200 lbf/in^2 must be admitted to raise the pressure in the drum to 100 lbf/in^2.

Neglect velocity of steam at entry and all heat losses. (H.N.D.)

16. 10 lb of steam of dryness 0·96 and pressure 120 lbf/in^2 expands adiabatically to a pressure of 12 lbf/in^2 and is then cooled at constant volume to a pressure of 2 lbf/in^2. Determine the dryness fraction of the steam at this pressure. If the steam is now condensed at this pressure until it reaches its original volume and is then heated at constant volume to its original pressure, determine the work done in the cycle, the heat taken in and the efficiency. Take $n = 9/8$. (H.N.D.)

17. A horizontal thermally insulated closed cylinder contains a frictionless non-conducting free piston. On one side of the piston is 1 ft^3 of dry saturated steam at 20 lbf/in^2. On the other side is 1 ft^3 of air at 60° F and 20 lbf/in^2 and this part of the cylinder contains a heating coil.

Heat is slowly supplied to the air until the pressure on both sides of the piston is 50 lbf/in^2.

(a) How much work is done by the air in compressing the steam? (The steam chart may be used.)

(b) How much heat is supplied to the air? (U. Lond.)

18. Steam is generated at a boiler pressure of 250 lbf/in^2 and the pressure is lowered by a reducing valve to 150 lbf/in^2 before supply to an engine. The dryness fraction on the boiler side of the reducing valve is 0·95, and the condenser pressure 2 lbf/in^2.

Using the Steam Tables, calculate (a) the dryness fraction of the engine side of the reducing valve, (b) the loss in work theoretically available, due to wire-drawing at the valve, expressed as a percentage of the Rankine heat drop from boiler pressure to condenser pressure.

(U. Lond.)

19. Steam at 50 lbf/in^2 is compressed according to pV = constant, to 150 lbf/in^2. Determine the heat to be removed during the process, if the original volume was 5 ft^3. (U. Lond.)

20. Adiabatic (isentropic) expansion of steam takes place between two state points a and b. Explain with the aid of a sketch of the corresponding pV diagram, the essential difference between the heat drop from a to b and the change of internal energy between the same two points.

Explain the fundamental difference between the Total Heat or Enthalpy of steam and the meaning of Q in the equation $Q = W + \Delta U$ where W represents the work done and U the internal energy.

Develop Clapeyron's equation for the specific volume of dry saturated steam:

$$(V_g - V_f) = \frac{Jh_{fg}}{T} \times \frac{dT}{dp}$$

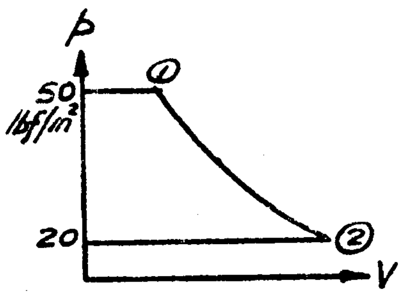
Use the equation to find the specific volume at 16 lbf/in² from the relevant data at 15 and 17 lbf/in². (U. Lond.)

Solutions

1. The internal energy of a vapour is the energy stored by virtue of the motion of the molecules of the vapour and depends on its condition.

The enthalpy may only be defined as the sum of the internal energy and the product of the pressure and volume.

Thus $h = u + pV$.



$$V_1 = V_g \text{ at } 50 \text{ lbf/in}^2$$
$$= 8{\cdot}516 \text{ ft}^3/\text{lb}$$

$$V_2 = V_1 \left(\frac{p_1}{p_2}\right)^{\frac{1}{1\cdot 1}} = 8{\cdot}516 \left(\frac{50}{20}\right)^{\frac{1}{1\cdot 1}}$$
$$= 19{\cdot}6 \text{ ft}^3/\text{lb}$$

V_g at 20 lbf/in² $= 20{\cdot}09$ ft³/lb

$$\therefore\ 19{\cdot}6 = 20{\cdot}09x + (1-x)[0{\cdot}01602 + 0{\cdot}000023g]$$