ADDENDA

page 157, lines 11 to 17 to read:

Calculate the bore of the low pressure cylinder of the reciprocating compressor to give the equivalent available energy for purposes of supercharging when the stroke-bore ratio of the compressor is 1.5, the compressor rotates at 400 rev/min and delivers air at 14 bar, 25 °C from suction conditions of 1 bar, 25 °C.

Take c_p and c_v for the exhaust gas as 1.25 and 0.98 kJ/(kg K) respectively and assume a volumetric efficiency of 100%.

page 157, line 24 to read:

For air at 1 bar, 25 °C

page 157, line 26 to read:

$$v_{\text{air}} = \frac{RT}{p} = 0.287 \frac{\text{kJ}}{\text{kg K}} \times \frac{298 \text{ K}}{100 \frac{\text{kN}}{\text{m}^2}} = 0.8553 \frac{\text{m}^3}{\text{kg}}$$

page 158, lines 1 and 2 to read;

$$\dot{V}_{\text{air}} = \dot{m}_{\text{air}} v_{\text{air}} = 0.211 \frac{\text{kg}}{\text{s}} \times 0.8553 \frac{\text{m}^3}{\text{kg}} = 0.1805 \frac{\text{m}^3}{\text{s}} = \frac{\pi D^2 L N}{4}$$

$$\text{or } D = \sqrt[3]{\frac{0.1805 \frac{\text{m}^3}{\text{s}} \times 4}{\pi \times 1.5 \times 400 \frac{\text{stroke}}{\text{min}} \left[\frac{60 \text{ s}}{\text{min}} \right]}} = 0.152 \text{ m}$$

APPLICATIONS OF ENGINEERING THERMODYNAMICS

APPLICATIONS OF ENGINEERING THERMODYNAMICS

A tutorial text to Final Honours degree standard

G. Boxer

*Senior Tutor in Mechanical Engineering
University of Aston in Birmingham*

© G.Boxer 1979

All rights reserved. No part of this publication may be reproduced or transmitted, in any form or by any means, without permission.

First published 1979 by
THE MACMILLAN PRESS LTD
London and Basingstoke
Associated companies in Delhi Dublin
Hong Kong Johannesburg Lagos Melbourne
New York Singapore and Tokyo

British Library Cataloguing in Publication Data

Boxer, George

Applications of engineering thermodynamics.

1. Thermodynamics - Problems, exercises, etc.

2. Heat engineering - Problems, exercises, etc.

I. Title

621.4'021'076 TJ265

ISBN 978-0-333-24354-1 ISBN 978-1-349-04041-4 (eBook)

DOI 10.1007/978-1-349-04041-4

This book is sold subject to the standard conditions of the Net Book Agreement.

The paperback edition of this book is sold subject to the condition that it shall not, by way of trade or otherwise, be lent, resold, hired out, or otherwise circulated without the publisher's prior consent in any form of binding or cover other than that in which it is published and without a similar condition including this condition being imposed on the subsequent purchaser.

CONTENTS

Preface	vii
Nomenclature	x
A Fundamental Approach to the Solution of Thermodynamics Problems	xiii
1 Reciprocating Gas Compressors and Motors	1
Geometry - Work Transfer - Volumetric and Mechanical Efficiencies	
2 Reciprocating Internal Combustion Engines	12
Geometry - Mean effective Pressure - Fuel consumption - Power output - Volumetric, Gravimetric and Thermal Efficiencies - Supercharging	
3 One-Dimensional Steady Flow in Ducts	28
Stagnation and Static conditions - Flow in Nozzles - Critical flow	
4 Radial Flow Compressors	42
Applications as Superchargers, in Refrigerators, in Gas Turbine plant - Mach Number and Prewhirl	
5 Axial Flow Compressors	51
Degree of Reaction - Number of Stages - Geometry - Polytropic Stage Efficiency	
6 Axial Flow Turbines	59
Impulse and Reaction Turbines - Geometry - Steam and Gas Plant - Power Output - 'Leaving Loss' - Reheat Factor - Polytropic Efficiency	
7 Gas Turbine Plant	71
Closed and Open Circuit plant - Pressure Ratio, Power Output and Thermal Efficiency - Limiting Values	
8 Turbo Jet Engine, Ramjet and Rocket	80
Ram effect - Thrust - Economy - Impulse - Efficiency - Mach Number - Subsonic and Supersonic Flow - Geometry	

9	Variable Specific Heat Capacities	91
	Analytical and Graphical Methods - Cycle Analysis - Effect on Power Output and Mean effective Pressure - Effect on Efficiency	
10	Dissociation	105
	Mol fractions in dissociation - Equilibrium Constant - Isentropic Index calculation	
11	Vapour Power Cycles	114
	Reheat - Regenerative Feed Heating - Process Heat Cycle - Nuclear Power Cycle - Power Output - Thermal Efficiency	
12	Vapour Compression Refrigerators	130
	Single and Multi-stage Cycles - Coefficient of Performance - Use of Pressure/Enthalpy Chart - Geometry	
13	Hygrometry, Air Conditioning and Evaporative Coolers	142
	Absolute and Relative Humidities - Use of Psychrometric Chart	
14	Further Work on Availability and Combined Cycles	154
	Irreversibility - Non-flow and Steady-flow calculations - Component contributions to Irreversibility - Combined Steam and Gas Turbine Plant - Diesel Engine and Vapour Power Cycle for Recuperative Purposes	

PREFACE

This volume like its predecessor (Engineering Thermodynamics, Theory, Worked examples and Problems - Macmillan 1976) is a collection of examples and worked solutions drawn mostly from the degree examination papers of London and Aston Universities.

The earlier book was intended as an introductory tutorial volume for first year undergraduates and those studying the subject at comparable level on other courses in which it was hoped that the right habits could be developed in demonstrating a unified approach to solving all problems in the subject. It included a one-page questionnaire designed to instil into the minds of students (by its continued use) the fundamental ideas so essential to a correct understanding of the subject.

I make no apologies for repeating the questionnaire here since it is equally relevant. This volume covers work up to final honours degree standard and the fundamental ideas of the subject do not change between first and final years. Indeed once the fundamentals are properly mastered the material of the succeeding years is very much easier to assimilate than if no unified approach is adopted.

Thermodynamics should not be subdivided into packets of theory as though they were seemingly unrelated and distinctive. The underlying ideas of continuity of mass, energy and momentum are true for all engineering applications and it is this that must first be properly understood.

I stress again as in the earlier volume the paramount virtue of attempting the problems without reference to the solution in the first instance. This is most important if the student is to teach himself and to find out where his weaknesses lie. The attractive and easy path of reading problem and solution together does not make for a ready understanding and must be avoided as only a fool's paradise.

Language is crucial to all good teaching and it must be clear, concise and consistent. One physical symbol should, as far as is possible, represent one physical idea. The trouble is, of course, that there are not enough symbols to go round so that some duplication is unavoidable. At this point I would apologise for two aberrations which do not accord with best practice. One is the use of 'd' rather than δ for use in the differential form of the energy equation with heat and work transfer:

i.e. $dq - dw = de$ which would better be expressed as

$$\delta q - \delta w = de,$$

since heat and work transfers are not properties but interactions. The second is the use of an upright suffix *s* relating to isentropic changes. This, of course, should have been an italic *s*, as in the main text, since this is a physical property of the system and has dimensions. As far as I am aware these are the only departures from what is now British Standard practice for the presentation of physical equations.

Dimensional reasoning, as pointed out in the earlier book, is vitally important, and again I stress the foolproof method of the use of Unity Brackets as a means of resolving dimensions in a calculation. Dimensions are by far more important than the numbers preceding them and all teachers face the ever-present problem of instilling into the minds of the students they take the vital need to check the dimensional balance of the equations they use. A physical equation is true in any system of units but a numerical equation must be checked for dimensions as in the following example.

$h_0 = h + \frac{1}{2}u^2$ for deriving stagnation enthalpy of a compressible fluid.

Assuming the fluid is a perfect gas and has a specific heat capacity at constant pressure c_p ,

then $T_0 - T = \frac{1}{2} \frac{u^2}{c_p}$ and the normal substitution of dimensions in SI gives

$$T_0 - T = \text{A number} \frac{\frac{\text{m}^2}{\text{s}^2}}{\frac{\text{kJ}}{\text{kg K}}}$$

which is not obviously a change of temperature in this form.

However, with the use of Unity Brackets we can transform this calculation quickly and unerringly so that it is so.

$$\begin{aligned} \text{Thus } T_0 - T &= \text{A number} \frac{\text{m}^2}{\text{s}^2} \frac{\text{kg K}}{\text{kJ}} \frac{[\text{N s}^2]}{[\text{kg m}]} \frac{[\text{kJ}]}{[\text{kN m}]} \\ &= \text{A number} \times \frac{1}{1000} \text{ K} \quad (\text{all others cancelling}) \end{aligned}$$

In this calculation it is the checking of dimensions which confirms that the method is correct since K is the unit of change in temperature. The system is foolproof and very powerful and is never vulnerable. It cannot be too strongly recommended and is used throughout this book. To try to guess where the various correcting factors are without the dimensions is to court disaster as the work obviously gets more sophisticated as we proceed.

A word on the units used for specific entropy and specific heat. These two have identical units but I feel it is worthwhile to distinguish between them by writing specific entropy in $\text{kJ}/(\text{K kg})$ and specific heat capacities in $\text{kJ}/(\text{kg K})$.

The use of kmol is now widespread and implies that mol refers to gram mole and that further k still means kilo and can be cancelled as in kg or kN . Thus m_w has the units g/mol .

Having tried to emphasise the unified approach to the solution of all problems in thermodynamics it may seem that I am splitting up the general syllabus of the subject into the very familiar sections of theory that one sees in nearly all books on the subject. We must remember, however, that the student needs some subdivision of material for reasonable assimilation and to avoid mental indigestion but he/she should continually refer to the questionnaire asking the fundamental questions about processes, the energy equation etc. on whatever the topic might be. Then the broad and sound basis will become apparent and the subject will make sense - much more sense than hitherto.

The solutions are very nearly exhaustive but some elementary work is assumed as being first year level which can reasonably be expected to be carried through at this stage.

The last chapter on availability and combined cycles covers examples of plant in current practice and does not examine the possible plant of the future. I have included one example on a fuel cell since although only small scale units have been made so far, the device holds out promise of rich rewards in the future.

Furthermore the type of combined plant that can be used in practice is very much a balance between capital and running costs and matching the steam and gas turbine plant is extremely important here. In all total energy systems the most effective use of fuel will be achieved when the energy delivered is divided appropriately between process heat and electrical power, the subdivision varying with each plant.

The advent of fluidised bed combustion boilers gives an opportunity to effect heat transfers at considerably lower temperatures with obvious benefits in corrosion but suffering the penalty inasmuch as it is 'Anti-Carnot'. It is a very active research area at present.

Most other attempts (e.g. Organic Rankine cycle) which aim at raising the availability output and reduce the inefficiency and therefore running costs suffer from the considerable increase in capital costs due to the expensive fluids involved.

Once again the choice of question and solution for such a book as this is a compromise between that which will adequately cover a reasonable range of material and that which will not prove too expensive to purchase.

I must mention here the omission of any heat transfer calculations since these form a subject in their right and have their own distinctive laws of radiation, conduction and convection.

Further reading around the subject is always advisable when attempting tutorial work both for consolidation and final revision and there is a wide choice among the several notable text books that have been published in the last ten years or so in England and in the Systeme International. Among these, those by Rogers and Mayhew and by Goodger are both excellent.

The University of London have once again been kind enough to allow me to draw on the examination papers of the now discontinued external degree in engineering and the responsibility for the solutions is my own.

Inevitably, I presume, there will be errors, particularly, as has been pointed out to me in the past, when a work of this kind is attempted single-handed. The ideal way is of course to use only problems which have been tried by a large body of students and are fully warranted as a result. Unfortunately, the time-scale for this book has not permitted this. I will, therefore, be most grateful for any correction that comes to light in the use of this volume. I would add that I am already in debt to those who have been good enough to send me their suggestions on the introductory volume and I hope that the second edition of this will embrace all of these.

My thanks go to Dr.J.R.Howard for an illuminating discussion on combined cycles and to Professor K.Foster for his encouragement and patience in a time of most pressing developments in our department.

NOMENCLATURE

A	Non flow availability or Area
a	Non flow specific availability (i.e. per unit mass)
B	Steady flow availability
b	Steady flow specific availability
c_p	Mass isobaric specific heat capacity
c_v	Mass isochoric specific heat capacity
$\bar{c}_p$	Molar isobaric specific heat capacity
$\bar{c}_v$	Molar isochoric specific heat capacity
d	change in
E	Internal energy
e	Specific internal energy
g	Gravitational acceleration or specific Gibbs function
H	Enthalpy
h	Specific enthalpy
h'	Specific enthalpy of two-component fluid
L	Length
M	Mach number
m	Mass
m_w	Relative molar mass
$\dot{m}$	Mass flow rate
N	Rotational speed
n	Polytropic index or number of mols
P	Perimeter
p	Pressure
Q	Heat transfer
$\dot{Q}$	Rate of heat transfer
q	Specific heat transfer
R	Gas constant
R_0	Universal gas constant
r	Compression or expansion ratio
S	Entropy
s	Specific entropy
T	Temperature
t	Time
u	Velocity
V	Volume
$\dot{V}$	Rate of volume flow
v	Specific volume
$\dot{W}$	Work transfer
$\dot{W}$	Rate of work transfer or power
w	Specific work transfer
x	Dryness fraction (quality) or mol fraction
z	Datum height

Suffices

a	Dry air
c	Compressor
f	Liquid state (saturated)
g	Vapour state (saturated)
i	Constituent or intermediate
m	Moist air
o	Reference state (also as a superscript)
p	Pressure constant
s	Entropy constant or steam
t	Total
v	Volume constant
w	Water

α	Absolute velocity angle
β	Relative velocity angle
γ	Ratio of specific heat capacities
ϵ	Electrical potential difference
η	Efficiency
θ	Temperature change due to fluid deceleration
Λ	Degree of reaction
μ	Chemical potential
ρ	Density
σ	Slip factor
ω	Angular velocity or absolute humidity
Σ	Sum of
$\oint$	Sum of round a cycle
ϕ	Relative humidity

A FUNDAMENTAL APPROACH TO THE SOLUTION OF THERMODYNAMICS PROBLEMS

The following is an attempt to assist students in adopting a rational approach to the solution of all problems in thermodynamics. If the following questions are correctly answered each and every time a problem is attempted there should be no fundamental difficulty in obtaining a solution.

1. What kind of *process*? (a) Flow or (b) Non-flow?

To answer this it is necessary to define the system boundary and/or the control surface and then decide whether mass crosses the latter.

2. What kind of *fluid*?
 - (a) Liquid?
 - (b) Liquid/Vapour Mixture?
 - (c) Saturated Vapour?
 - (d) Superheated Vapour?
 - (e) Perfect Gas?
 - (f) Semi-perfect Gas? (i.e. with variable c_p and c_v sometimes referred to as an ideal gas)

3. Have you drawn a *state diagram(s)*?

Have you drawn a *flow diagram* in the steady flow case?

It is vitally important to get a *picture* of events.

4. Which form of the *energy equation* is required?

- (a) Non-flow?
- (b) Steady-flow? (remembering also the reduced form which is most common i.e. ${}_1q_2 - {}_1w_2 = h_2 - h_1$)
- (c) Unsteady flow?

5. Do you need to use the *Mass Continuity* equation?

$$\dot{m}v = uA$$

6. Do you need to use the *momentum* equation?

7. Have you used the correct language? (i.e. symbols AND units)

e.g. w in kJ/kg, w in kJ, $\dot{w}$ in kW, etc.

8. Always put in *dimensions* with the numbers in your reasoning.

Dimensions are a vital check on your arguments and are more important than the numbers in front. Use *Unity Brackets* to rationalise the dimensions.

9. Do not effect *numerical calculation* until you have to.